# Allocation and Routing of CRAF MD80 Aircraft

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# Allocation and Routing of CRAF MD80 Aircraft

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Operations Research

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March 1990

## Preface

Airlift has and always will be an integral part of this country's defense posture. My experience as an airlift pilot drew me to this topic dealing with a very special part of our airlift forces, aeromedical evacuation. This thesis attempts to make a "first cut" in the analysis of how the new Civil Reserve Air Fleet (CRAF) aeromedical evacuation mission should operate.

My thanks goes to Captain Keith Ware of the MAC Command Analysis Group (HQ MAC XPY) for taking time out of his busy schedule to provide needed data and information. He was also an invaluable link to MAC Plans (XP) and the MAC Surgeon General (SG).

I am also indebted to my thesis advisor, Dr. Yupo Chan, for his supervision of my effort. His great depth of knowledge in this area has truly been appreciated. Many times his insights have kept me from wandering down dead ends.

Finally, I must thank my wife, Laurie, and my daughters, Gwen and Justene, for their understanding and support over this past year and a half. I have truly been blest with a wonderful family.

William Brand Carter

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## Abstract

The purpose of this ~~study~~ was to provide information for a plan of operations for the future Aeromedical Evacuation System. This future system will use Civil Reserve Air Fleet Boeing 767 and McDonnell-Douglas MD80 aircraft to evacuate injured personnel from the area of conflict to the continental United States. The study had three basic objectives dealing with the stateside distribution of patients by MD80 aircraft: (1) Allocation of the MD80s among the nine stateside hubs; (2) Average worst-case routing of MD80s to depict the most likely routes; and (3) Investigate the 2- and 3-dimensional spacefilling curves as useful real time routing tools for such an operation.

Allocation was handled using a spreadsheet application to evenly distribute the six different categories of patients among the 52 National Disaster Medical System coordination centers. A simulation network was developed to determine each hospital's ability to handle the allotted patients. The distribution of MD80s was then determined using the average daily number of patients needing transportation to locations other than the hubs themselves. It was determined that the limiting number of 30 MD80s would

not constrain the transportation network. In the worst scenario, only 27 MD80s were required.

A vehicle routing model, based on a previously proven probabilistic travelling salesmen formulation (with vehicle capacity constraints added), was used to determine the worst case average routes. Each hub represented a separate problem. When the math model grew to be too large for existing application software, a 3-dimensional spacefilling curve heuristic was employed. The results from this heuristic compared favorably with a parallel effort utilizing the Clarke-Wright algorithm.

The 2- and 3-dimensional spacefilling curves proved to be excellent routing tools. The 3-dimensional curve (with hospital demand as the third dimension) required less interpretation to arrive at suggested routes. The 2-dimensional curve required the additional application of a nearest neighbor heuristic.

# Chapter I. Introduction and Background

An important part of our country's warfighting capability is the ability to evacuate injured troops quickly and efficiently. This not only saves lives, but directly affects the morale of the fighters themselves and indirectly affects the attitude of the country's populace.

Since 1949, the policy of the U.S. Armed Forces has been to move war casualties from the conflict theater to the United States via air transportation. In that year the Secretary of Defense issued the following directive:

> In both peace and war, the transport of patients of the Armed Forces shall be accomplished by aircraft when air transportation is available and conditions are suitable for air evacuation unless medically contraindicated (13:9).

The war in Vietnam was proof that aeromedical airlift worked. The Air Force Surgeon General at that time, Lt. General Kenneth Pletcher, remarked, "thousands of US fighting men are alive today because speed, new techniques, and trained personnel of aeromedical evacuation teams are giving the wounded in Vietnam better than twice the chance of survival than ever before" (13:10-11).

## The Current Aeromedical Evacuation System (AES)

Aeromedical evacuation is the responsibility of the

United States Air Force's Military Airlift Command (MAC). To carry out this mission, MAC maintains a fleet of 18 McDonnell Douglas C-9A "Nightingales." In time of war these aircraft would continue to operate as they do in peacetime, distributing patients within the United States. MAC C-130 aircraft, configured for aeromedical airlift, would deploy to the conflict theater to carry out the in-theater airlift of patients. Patients would then be moved from the theater to the United States by Lockheed C-141 "Starlifters" (1:1).

In 1984, Headquarters MAC conducted a Patient Distribution-Redistribution Study (PDS). This study was based on comparing the European casualty estimates against the planned wartime C-141 flight schedule. The most significant result of the PDS was the discovery that the current planned strategic aeromedical evacuation by C-141 had a large shortfall in capability to airlift litter patients (12:7).

The use of the C-141 for patient evacuation presents another dilemma. The C-141 is currently the mainstay of the strategic airlift force. In time of war the major mission of C-141 units is to deploy Marine, Army and Air Force units to the area of battle. The added mission of aeromedical evacuation requires the C-141s to use more ground time to reconfigure from an aeromedical configuration to a cargo configuration, and vice versa. This increase in ground time increases closure times, thus causing our fighting forces to be delayed in getting to their deployed locations (closure being the time it takes to deploy a fighting unit from the U.S. to the area of conflict)(10:312-315). In the overall scheme of war readiness, this means the enemy is allowed to advance further because we cannot get our forces in position in time. To decrease closure times it is necessary to eliminate any extra time created by the strategic aeromedical airlift mission (18).

## The Future Aeromedical Evacuation System

On 28 May 1986, the Office of the Secretary of the Air Force, with Congressional approval, authorized MAC to, in time of war, shift the aeromedical airlift mission to the Civil Reserve Airlift Fleet (CRAF) (12:7). MAC has negotiated with the national airlines to provide 85 Boeing 767 airframes equipped for air evacuation. The U.S. government pays these airlines for the cost of making the necessary modifications and for any additional costs that arise from having a CRAF-capable airframe (18).

The future wartime aeromedical evacuation system (AES) is to work much like the current hub-and-spoke system the larger national airlines use. The C-9s will fly the spokes in the theater of conflict delivering patients to the overseas hubs. The 767s will fly these patients to hubs in the U.S. These hubs are strategically located near large National Disaster Medical System (NDMS) hospitals. When the NDMS hospitals at the hubs are fully utilized, arriving patients will wait in staging areas for an available McDonnell-Douglas MD80. These aircraft will distribute patients to other smaller NDMS hospitals in the U.S., completing the hub and spoke AES (18).

Currently, the details of the MD80 operations have yet to be worked out. The MD80s, like the 767s, will be CRAF airframes. At the present time MAC predicts 30 MD80s will be available for this purpose (12:7).

The MAC Surgeon General (SG) has overall responsibility for the AES. Currently, MAC SG has chartered the MAC Analysis Group (XPY) to study different ways of making this proposed system as efficient as possible. MAC XPY has been devoting its time and effort to the 767 concept of operation. They are extremely interested in any work that can be done to help develop plans for the allocation and routing of the MD80s. Therefore, it is the intent of this thesis effort to aid in this endeavor.

## Research Problem

The problem is how to initially allocate and route the MD80s in order to cover the most probable distribution of patients needing transportation to outlying hospitals. The goal of MAC SG is to efficiently utilize the CRAF MD80 assets while moving the expected patient loads. After developing an initial allocation and routing for plans purposes (plans as in "Operations Plans" or OPLAN), the next follow-on problem is to develop a means to route MD80 aircraft once the real-time flow of patients begins.

From a theoretical point of view, the routing portion of this problem is a stochastic vehicle routing problem with multiple depots. In this case, there are nine depots and 30 vehicles corresponding to nine stateside hubs and 30 MD80s. Since MAC has already determined the locations of the hubs and their associated servicing hospitals, the problem is simplified to nine individual stochastic vehicle routing problems. Aircraft allocation is determined simply by the expected flow of patients through the hub. The different types of patient categories are also an additional complication to the stochastic nature of this problem. MAC categorizes patients into 6 types depending on the nature and severity of their wounds (18). Thus, each patient type can be considered a separate "commodity."

## Scope of the Research

The scope of this effort will include only the stateside movement of patients. It will be assumed 40 Boeing 767s arrive each day to the United States. This is the projected "worst case" MAC has determined (21). Each hospital has a certain capability to handle some or all of the 6 categories of patients. It will be necessary to not only know the capacity of a hospital, but also to know what categories and how many patients in these categories the hospital can handle.

Since a full-scale war has not occurred in recent time (a war taking into account current technology), patient data is non-existent for this problem. Therefore, this effort will have to rely on the expected casualty figures determined by the U.S. Army for a European war. These are the same figures MAC used in their PDS and in determining the nine hubs for the 767s (18).

Since airline in-service rates for aircraft are extremely high, this effort will assume maintenance on the 30 MD80s will not affect the problem. This means, at all times, 30 aircraft will be available to fulfill their CRAF mission. Along with this is the assumption that once an aircraft is allocated to a certain hub, it will operate from that hub only. In other words, the MD80s will not interfly between the hubs. This is MAC's intention and it simplifies the problem by eliminating connections between hubs (18). In reality, an MD80 from a neighboring hub could be scrambled to an overloaded hub to aid in distributing patients. Also, it is possible for an occasional MD80 to distribute patients between hubs if the need arises.

The next chapter discusses the current literature applicable to this research effort.

## Chapter II: Literature Review

As previously mentioned, the operations research methods applicable to this problem fall under the classification of vehicle routing problems (VRPs). This classification can be further broken down into the categories of deterministic VRPs and stochastic VRPs. For planning purposes, MAC is interested in the most "probable" routing and allocation of the MD80 assets. After this, an actual routing method would be their next desire. This method should be simple enough for daily use by scheduling personnel, yet accurate enough to assure near-optimal transportation of patients with the given number of aircraft. Both of MAC's requests are based on probabilistic information. Therefore, the stochastic vehicle routing methods are the most applicable. This literature review will cover current models and information in this area, starting with a formal statement of the vehicle routing problem.

Chan and Rowell give a comprehensive description in their survey of location and routing problems. In the following, taken directly from their work, i represents the departing node and j represents the arriving node. Both are in the set of all nodes, I. The variable x has a value of 0 if the arc (leg) from i to j is not taken, and a value of 1 if it is. Parameter f is the demand at a node. Parameter $d_{ij}$ is the cost (distance or time in this case) of travel between nodes i and j. $|H|$ represents the total number of vehicles in the set H (h is each vehicle). Finally, J is the set of nodes already visited.

Formal Statement of the Vehicle Routing Problem (8:12-14)

Formally stated, if delivery requirements are placed upon the various demand points of a travelling salesman problem, one ends up with a "vehicle routing problem." The multi-vehicle-type version can be stated as having a set of lowest cost tours:

$$\text{minimize} \sum_{i \in I} \sum_{j \in I} \sum_{h \in H} d_{ij} x_{ij}^{h} \qquad h=1,2,\ldots,|H| \; ; \tag{1}$$

where H is the set of vehicle types ranging from h = 1,2,....$|H|$.

The first two constraints ensure that each demand point is served by only one vehicle:

$$\sum_{i \in I} \sum_{h \in H} x_{ij}^{h} = \begin{cases} |H| \text{ if } j=1 \\ 1 \text{ if } j=2,\ldots,|I| \; . \end{cases} \tag{2}$$

$$\sum_{j \in I} \sum_{h \in H} x_{ij}^{h} = \begin{cases} |H| \text{ if } i=1 \\ 1 \text{ if } i=2,\ldots,|I| \; . \end{cases} \tag{3}$$

Route continuity is maintained for all vehicle types:

$$\sum_{i \in M_p} x_{ip}^{h} - \sum_{j \in \overline{M}_p} x_{pj}^{h} = 0 \qquad \forall h, \; \forall p \in I \; . \tag{4}$$

Vehicle capacity constraints are enforced for each vehicle type as it picks up traffic along the tour:

$$\sum_{i \in I} f_i \sum_{j \in I} x_{ij}^{h} \le v_h \qquad \forall h \; . \tag{5}$$

Constraints are placed upon the maximum "time" $U_h$ a vehicle h spent "on the road":

$$\sum_{i \in I} t_i^{h} \sum_{j \in I} x_{ij}^{h} + \sum_{i \in I} \sum_{j \in I} d_{ij}^{h} x_{ij}^{h} \le U_h \, , \tag{6}$$

where $t_i$ is the amount of time the vehicle spends at a demand point and $d_{ij}$ is now interpreted as the "link time" from i to j.

The next two constraints guarantee that vehicle availability is not exceeded at depot 1 for each type of vehicle h:

$$\sum_{j \in M_1} x_{1j}^{h} \le 1 \qquad \forall h \; , \text{ and} \tag{7}$$

$$\sum_{i \in M_1} x_{i1}^{h} \le 1 \qquad \forall h \; . \tag{8}$$

Connections (regardless of vehicle type) to constitute a tour is ensured by the subtour-breaking constraint

$$\sum_{i \in J} \sum_{j \notin J} \sum_{h \in H} x_{ij}^{h} \ge 1 \; . \tag{9}$$

Vehicle Routing Models

The first vehicle routing problem formulation to be reviewed is Laporte's Multi-Depot/Multi-Tour Problem. Chan and Rowell describe this model in their survey of location and routing problems. This model is applicable because it optimizes both the number of vehicles and the routing of these vehicles from each depot (8:19-21). Chan and Chrissis review the algorithm for this model. Capacity restrictions are handled in the subtour-breaking and chain-barring constraints. It also optimizes the depot locations (7:5-10). By removing this last aspect of Laporte et al's formulation, an easier formulation could develop.

Another formulation mentioned in Chan and Rowell's work is one by Perl and Daskin. This formulation takes into account the supply source to all the depots (8:21). For this research the patients are all coming from one area, the war zone, via 767 aircraft. This equates to the single supply source serving the nine hubs or depots.

One aspect of this research is that the 767 part of the AES is being determined separately. This means each hub may be dealt with separately as a problem of finding how many aircraft are needed to serve that particular area and what routes each aircraft should fly. Chan and Rowell also describe a formulation by Federgruen and Zipkin where a single depot serves a number of locations. This formulation takes initial inventory values from each location and then fits vehicles and their routes to deliver additional "produce" (8:18-19). For this research the initial inventories could be the number of beds (per category) currently filled at a location and the "produce" could be the patients. The only difficulty with this formulation is that it does not take into account an upper bound on the number of additional patients a hospital location can take.

Dror, Laporte and Trudeau describe several stochastic vehicle routing models in their article "Vehicle Routing With Stochastic Demands: Properties And Solution Frameworks." They further divide stochastic models into two types. Chance constrained models are those where the objective is to find the route with the least probability of failure due to over-extending the capacity of the vehicle. Recourse models take into account the back and forth travel of a vehicle when capacity of the vehicle is expended or exceeded whichever the case may be. The difference in the two approaches is in the penalty functions. A chance constrained model penalizes on capacity mistakes while recourse models penalize on distances traveled when route "failures" occur (11:170-171).

One chance constrained model, developed by Stewart and Golden, bases its solution on the obvious fact that the optimal solution to any VRP is a feasible (but maybe not optimal) solution to the associated multiple traveling salesmen problem (11:171) (A multiple traveling salesmen problem (MTSP) seeks the minimal distance routes among locations for a given number of salesmen. Capacity is not a consideration). This is an important point since it means the optimal solution to the multiple traveling salesmen problem for a given set of locations is therefore the super-optimum, or a bound, on the VRP. In other words, the best solution to any VRP cannot be less (if distance is the measure) than the associated MTSP. This suggests solving the MTSP first and then trading legs between separate salesmen until capacity constraints are met.

A recourse model (Laporte and Louveaux) was also presented in which all customer (hospital) demands are known before the aircraft leaves the hub. An initial set of previously determined routes are then modified to fulfill the requirements. They do mention though, "For problems of realistic dimensions the size of this formulation precludes solution by exact methods" (11:172). It seems the need for a suitable heuristic is required.

Several studies have been done that are similar in some aspects to the problem in this research. The first of these was a study done by several members of the Studies and Analysis section at MAC Headquarters. This was a routing, allocation and location study for the C-23 European Distribution System (EDS) aircraft. The method used to optimize the operations of the EDS aircraft was to first break the problem into its separate parts. These parts are the three problems of operating location selection (to include servicing locations for each operating location), multiple aircraft routing, and multiple location routing.

Basically, after determining how many basing locations and where these basing locations should be, next determine which servicing locations should be handled by each basing location (facilities served by each depot). To do this, a linear program where one aircraft was assigned to each basing location was used. Each aircraft had to be used and it had to start and end its route at its assigned operating location. Finally, each route could not transit more than one basing location (15:19-20). The optimal solution to this formulation divided up all the servicing locations and assigned each one to an individual basing location. Since the locations for basing the MD80s and the servicing destinations for each base (hub) have already been determined, the remaining steps of the solution approach greatly resembles the object of this thesis; mainly, allocation and routing.

The final step to the EDS problem was to determine how many aircraft each basing location should have and the optimal routes they should fly in order to cover the assigned servicing locations. This was accomplished using a multiple traveling salesmen formulation with the number of salesmen being a bounded variable (15:14).

The major drawback to this solution approach when compared to the objectives of this research is the lack of consideration for aircraft capacity. They do make mention of capacity restrictions stating, "However, when the MTSP (multiple traveling salesmen problem) is expanded to include vehicle capacity and total route length or cost restrictions, CHRISTOFIDES, MINGOZZI, AND TOTH claim that the largest problem solved exactly contained only 25 bases" (15:19). Once again, since this thesis effort deals with 52 total locations (basing and servicing), this quote seems to suggest a heuristic method will be necessary.

Another similar work was accomplished by Major Dave Merrill in his thesis to determine the best single location and routing structure for MAC C-29 Flight Check aircraft. In his effort to efficiently route aircraft to demand sites, he developed a modified stochastic multiple traveling salesmen formulation. As mentioned earlier in Stewart and Golden's chance constrained VRP the MTSP is at the heart of the VRP. Merrill's modified formulation performed well when the number of sites to visit, including the home base, was less than or equal to 7 (16:32). Since 7 out of the 9 hubs are less than 8 nodes each, this thesis effort will prosper by Merrill's modified formulation which follows (18).

This formulation is taken directly from Merrill's work. To clarify, the K in Equations (11) and (12) should be |K| (the total number of aircraft). K represents the set of all aircraft and therefore can not be a "number."

<u>Merrill's Formulation</u> (17:2-3)

$$\min \sum_{i \in I} \sum_{j \in I} d_{ij} x_{ij} \tag{10}$$

$$s.t.\ K \geq \sum_{j \in M_1} x_{1j} \geq 1 \tag{11}$$

$$K \geq \sum_{i \in N_1} x_{i1} \geq 1 \tag{12}$$

where K is the set of all aircraft, M is the set of nodes emanating from the depot and N the nodes incident.

$$x_{ij} + x_{ji} \leq 1 \qquad \text{for all } j \text{ (} j \text{ not equal to 1)} \tag{13}$$

$$x_{ij} + x_{ji} \leq 2 \qquad \text{for } j = 1. \tag{14}$$

The above states that a trip must enter and leave a demand node via different ways except to and from the depot.

$$\sum_{i \in N_j} x_{ij} = 1 \quad \text{for all } j \text{ except the depot } (i \neq j) \tag{15}$$

$$\sum_{i \in M_j} x_{ji} = 1 \quad \text{for all } j \text{ except the depot } (i \neq j). \tag{16}$$

These constraints force exactly one entry and one exit to and from every node other than the depot.

## Other Useful Information

Another interesting part of Merrill's thesis was the use of a Spacefilling Curve (SFC) Heuristic to determine the routing of multiple aircr ft. Bartholdi and Platzman describe using the SFC to solve the single traveling salesman problem. Here, locations to be visited are plotted on the unit square and then mapped to the unit interval via a SFC (3:294). The order the locations appear on the interval are the order in which they should be visited. Merrill expanded this heuristic to include the multiple salesmen case. He determined that groupings of points on the unit interval could be divided among the salesmen. For his study, this method resulted in routings no more than 10% greater than optimal (16:65-66). Platzman and Bartholdi claim for any number of points the worst is 25% over optimal (2:124). The appeal of the SFC approach is in its speed. It can give a "good" answer in a fraction of the time it takes to run a complete linear program. It can also give answers where a mathematical program may not be able to (16:64). Finally, it is also quite easy to program the heuristic. If the MD80s are to operate on a soft (flexible) schedule, the SFC heuristic would be an appropriate tool to determine routes and also to make quick changes when the need arises (as it often does in real situations).

As with the EDS study, Merrill's study did not take into account aircraft capacity. His thesis dealt with only a 2-dimensional SFC. Platzman and Bartholdi make reference to using a 2-dimensional SFC to solve various vehicle routing problems also. They concede the fact that VRPs are "more complex than the TSP" but that even VRPs can be "relatively easy to solve (via heuristics such as "nearest neighbor") after the problem has been converted to the interval" (3:296). They also mention that any dimension can be mapped to the unit interval via a SFC (3:292-293). They go on to reference two instances where this has been successfully done (3:295-296). Therefore, it could be possible for hospital demand (which directly affects capacity) to be considered as another dimension. This could produce the needed heuristic necessary to incorporate the capacity constraint into the MTSP, making it a VRP.

Some of the hospitals serviced by a particular hub are within 100 miles of each other. MAC considers this distance suitable for ground transportation (21). This means if an MD-80 is carrying patients for both these hospitals, MAC would prefer the plane visit only one of the two locations instead of flying the unreasonably short leg between the two locations. Current and Schilling describe a covering salesman problem formulation that would pick an optimal route based on this situation. This formulation basically scans each destination for other destinations within a prescribed radius, then uses this information to develop the shortest route (9:209-211). Once routes are determined by other means, this model could be used to eliminate unnecessarily short hops.

Finally, to better understand the traveling salesman problem (since it seems to be at the heart of this problem), a basic algorithm for its solution was reviewed. To take into account the probability of visiting a location, Bertsimas suggests it is much easier to determine a route deterministically and then work from this solution than it is to compute the optimal route in every instance by means of a probabilistic traveling salesman formulation (4:187). The most widely used algorithm for solving the deterministic TSP is one where the subtour breaking constraints are relaxed and a simple assignment problem is solved. A branch-and-bound technique is then applied where subtours are determined. One leg of the subtour is arbitrarily set to a prohibitive value, then the assignment problem is solved again. This is continued until the optimal route is found (14:125). From this description it is easy to see with increasing numbers of locations this algorithm can increase exponentially in solution time. As long as numbers of locations are kept small, it is an efficient way to determine optimal routing. This algorithm could possibly be used to test solutions generated through a SFC technique.

Summary

This chapter has presented the current and most applicable techniques relative to this problem of allocating and routing medical evacuation aircraft. It began with a review of the most general formulations and proceeded to the more specific. Many of these formulations are difficult to implement on the kind of computer hardware available to aeromedical airlift operations personnel. Therefore, the heuristic technique of the spacefilling curve was discussed and will be explained further in the following chapter. Other operations research tools such as spreadsheet techniques and simulation, will be used to arrive at input for the formulation to this problem. These too will be discussed thoroughly in the following chapter as the methodology is presented.

## Chapter III: Methodology

### Development

There are several possible ways to approach this research problem analytically. For this problem, we are considering the probabilistic movement of numbers of different types of patients to hospitals constrained by available capacities for the various types of patients. This movement is also constrained by the capacity of the MD80 and the total number of MD80s. Considering the objective of optimizing probabilistic tours (multiple and minimal length) for each hub, a linear programming approach appears to be the most suitable. When considering a patient cannot be fractionalized, the problem becomes a mixed integer program approach. This is a greatly simplified view of the overall approach to the problem.

### Data

The first real struggle is getting the data into a useable form. To date, the Military Airlift Command Analysis Group (MAC XPY) has determined the nine hub locations for the continental U.S. They are the cities of Los Angeles, San Francisco, Denver, Houston, Chicago, Atlanta, Charlotte, Philadelphia, and Boston. They were chosen based on either their centralized location or their overwhelmingly large patient capability (19). These locations are where the Boeing 767s will be bringing patients for either distribution to a hospital in the local area or for MD80 pick-up. Appendix B lists each "hub" and the outlying hospitals it serves. The term "hospital" should not be taken to mean a single building or complex as is usually associated with the word. In this research, "hospital" refers to the NDMS coordinating office responsible for distribution of patients to a group of hospitals located in the immediate geographical area. These areas are cities or military bases. MAC XPY and MAC SG have provided the following patient and aircraft data.

First, the six patient categories are defined as; (1) general medical (designated "MM"), (2) psychological ("MP"), (3) surgical medical ("SS"), (4) orthopedic ("SO"), (5) spinal injury ("SC") and (6) burn injury ("SB")(19). Appendix B lists, for each hospital, the capacity in each of the 6 patient categories and the hospital's total capacity.

The number of patients to expect in each category was given as a percentage of the total injured over the course of a war. The average recovery times are for a single patient. Although a standard deviation was not calculated when this data was taken, MAC SG suggested a standard deviation, if needed, would be roughly 10% of the mean (21). Table I, Patient Percentages and Recovery Times, lists the MAC-supplied information.

Table I: Patient Percentages
And Recovery Times (21)

| Patient Category | | Percentage of Total | Average Recovery Time per Patient (days) |
|---|---|---|---|
| General Medical | (MM) | 12.6% | 16 |
| Psychological | (MP) | 3.2% | 29 |
| Surgical Medical | (SS) | 44.1% | 24 |
| Orthopedic | (SO) | 36.8% | 50 |
| Spinal Injury | (SC) | 0.7% | 38 |
| Burn Injury | (SB) | 2.6% | 33 |

The MD80 aircraft data, except for the single aircraft capacity of 48 patients, was insignificant to the formulation of the problem. It was necessary to know the minimum runway length of 8000 feet in order to choose the appropriate airfield to service the hospital locations (20). Appendix A lists the identifiers for the airports used to service the appropriate areas. For example, the airfield at Ft. Leavenworth is a mere 5000 feet long. Therefore, neighboring Kansas City International was the nearest airport with over 8000 feet of runway. The range of the aircraft was of no significance for this thesis because all of the possible legs considered are well within half of the aircraft's worst-case range of 2000 miles (20). Also considered along with the aircraft is the crew limitations. A standard crew configuration would be able to handle a maximum crew duty-day of 16 hours, or 12 hours if the autopilot is inoperable. When crew alerting and preparation is deducted from this, the total time an aircraft can be off station with a single crew is 14 hours or 10 hours if at anytime during the off station tour the autopilot fails and suitable maintenance is unavailable at the enroute stops (21).

MAC XPY is continuing research into the concept of operations for the 767s. The current plan, according to MAC SG, is to distribute the incoming patients as evenly as possible among the nine hubs. MAC XPY predicts 30-40 767 fights will arrive to the U.S. daily (19). Since each 767 can carry a maximum of 111 patients, for a worst-case of 40 flights a day, this equates to 4440 patients per day in a worst-case scenario (11:8).

## Measurement and Analysis Criteria

Time and distance are the measurable criteria for this study. Appendix A contains a list of all hospital locations in alphabetical order and their latitudes and longitudes. To determine the MD-80 flight time between locations, the great circle distance between locations is calculated using the following two equation sets. The first set converts the latitude and longitude of a location into coordinates in the 3-dimensional x, y and z space. The radius of the earth (R) is 3441 nautical miles. The second set calculates the great circle distance between two points, where $x_1$, $y_1$ and $z_1$ are the coordinates of one location and $x_2$, $y_2$ and $z_2$ the coordinates of the second location.

$$X = R\cos(latitude)\cos(longitude)$$
$$Y = R\cos(latitude)\sin(longitude) \tag{17}$$
$$Z = R\sin(latitude)$$

$$Arc\ Distance = [(X_1-X_2)^2+(Y_1-Y_2)^2+(Z_1-Z_2)^2]^{\frac{1}{2}} \tag{18}$$

With this distance the following chart (Figure 1) provides the block hours for that particular leg. This chart uses 300 nautical miles per hour as the average speed of the MD80. Using 300 nautical miles per hour as a ground speed is a common and accepted "rule of thumb" used by most jet transport pilots to quickly estimate takeoff to landing flight times without having to figure in the affects of winds, routing, and departure/arrival maneuvering. Block hour is a more appropriate time to use for the purposes of this research because it takes into account the time an aircraft spends taxiing to and from the "gate." Times are calculated to the nearest hundredth of an hour.

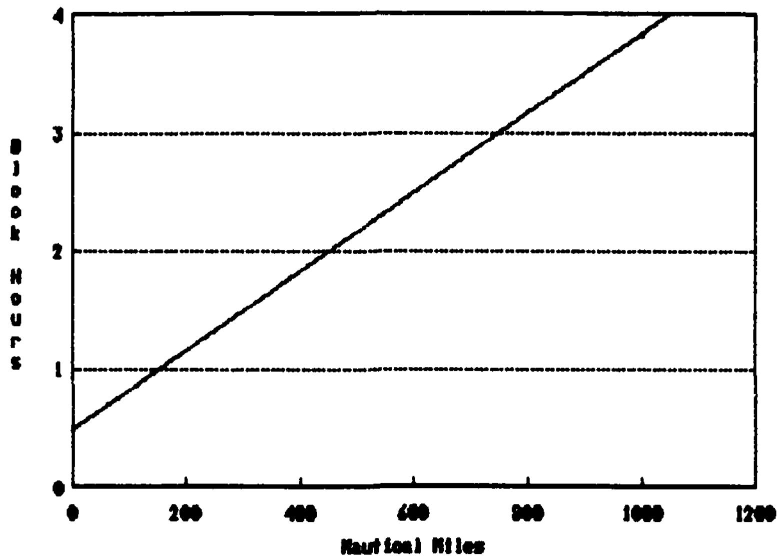



Figure 1. Curve for Determining Block Hours

Approach Methodology

The first step is to convert the data into a useable form. This is accomplished using Quattro™ (a spreadsheet) to first convert the spherical coordinates of latitude and longitude of each location into a three-dimensional coordinate in x, y, and z as per equation set (17). Next, using these coordinates, Quattro computes the great circle distances between each hub and its spoke locations plus the distances between each spoke location and the remaining locations in its individual hub network. Equation (18) provides this information. These are displayed in nine small matrices, one for each hub and its associated hospitals. From here the simple conversion to block hours will be made.

The second step is determining how many patients per day can be expected at each hospital in each category. This will also be done on a spreadsheet. First, the total number of beds in each category for a given hub (servicing locations included) is calculated. Next, the 4440 expected patients are proportionally distributed among the hubs. Proportionally distributed means, for example, if Chicago has 60% of the General Medical beds and Charlotte 40%, then 60% of the General Medical patients will go to Chicago and the remaining 40% to Charlotte. This gives the total number of patients to expect at each hub. The above process is then repeated in order to distribute the patients evenly among the hospitals within the individual hubs. Finally, the total of the categories for a single hospital gives the expected number of patients requiring transportation to that hospital for each day. This will also be referred to as this hospital's demand.

Another request from MAC Headquarters was to provide information on shortages, whether it be in aircraft or patient beds. The next step is important to the outcome of the routing structure. It also provides critical additional information as to how well each hospital can handle its expected demand in each category. Utilizing a simple SLAM simulation, the probability that a specific hospital can handle its daily inbound load can be determined. Obviously, the hospital is limited by the number it can serve. The simulation is comprised of six zero-capacity queues (for the six categories). Each queue precedes a number of servers representing the number of beds a hospital has in a specific category. Patients arrive daily to the queues and are placed in beds if they are available. Patients arriving and finding no beds available balk. Various data is collected in order to determine where shortages occur. The total number of patients served divided by the total number arriving provides a "performance indicator" for each hospital. This also effectively takes care of the multi-commodity aspect of the problem. The aircraft does not care what kind of patient it is carrying, it only cares how many.

What does this performance indicator depict and how could it affect MD-80 routing and allocation? This indicator is a measure of each hospital's capability to handle its projected "worst-case" load. For the purpose of the problem formulation this performance indicator is multiplied by the demand in order to arrive at a more realistic "worst-case-average demand" for each specific hospital.

With the data in a manageable form, the determination of allocation and routing can begin. At first glance the overall problem fits nicely into Laporte et al's formulation mentioned previously. This formulation has a single source to supply the hubs with "items" for dispersion to the surrounding demand locations. The formulation provides answers as to where to place the hubs, how many hubs are necessary, how many vehicles to base at each hub and how to route these vehicles based on not exceeding capacity limits.

There are two difficulties in this formulation when applied to the specific problem at hand. First, the formulation is purely deterministic. It is based on satisfying set demands at each location. The second difficulty with this formulation is that it chooses the hubs and each hub's servicing locations based on minimizing the route lengths and maintaining vehicle capacity constraints. Since hubs and servicing locations are already determined for this problem Laporte et al's formulation is unnecessary.

The overall problem is actually nine separate problems. Each hub must be examined separately to determine the routes necessary to fulfill demands; these routes being limited by total crew operating day and vehicle capacity. The constraint on all nine of these problems is the limit of the 30 MD80s available.

Considering MAC's request to assign aircraft to the individual hubs but not to interfly between hubs, allocation becomes a simple problem solved through enumeration. Only one additional assumption is made. Since the "worst-case" crew duty day is 12 hours with 10 of those associated with aircraft operations, it is assumed that the maximum utilization of each aircraft is two missions (each mission with one crew) per day.

Each mission can carry a maximum of 48 patients. To determine the total number of missions flown from a single hub in one day, the expected demands of the outlying hospitals are totalled and divided by 48. The resulting number is simply divided by 2 (since each aircraft can fly 2 missions per day) and rounded up to the nearest integer. This final value is how many aircraft should be allotted to that hub. Once all hubs are determined in this manner, all the values are summed. If this results in a number greater than 30, a more exacting approach needs to be applied and the added assumption dropped.

The next step is to determine the "probable" routing for the allocated MD80s. According to Dror, Laporte and Trudeau, stochastic vehicle routing problems (SVRPs) are divided into two types. The "wait and see" situations are problems where the routes are determined after the demands have been observed. They tend to degenerate into a simple vehicle routing problem (VRP). The second situation, "here and now," is where routes are set on anticipated demands. This is the situation this problem faces (11:170).

There are two types of formulations for "here and now" situations. The first is called a recourse model and is not applicable to this problem because it optimizes on traveling the shortest distances to and from the hub when route failures occur (11:171). This will never be the case, for all demands will be known in this problem. Therefore route failures will never occur in real-time operations. An example of the second type formulation is Stewart and Golden's chance constrained model. Here the routes are chosen strictly based on probable demand. If route failure occurs (meaning the aircraft is over capacity) the aircraft must return to the hub, reload, and finish the assigned route. There is no penalty for failure as in a recourse model. Instead, this model will "minimize distance traveled while controlling the probability of route failure" (11:171). In many respects it resembles a simple VRP where the probabilistic demand replaces the deterministic demand.

The objective is to minimize the total distance flown by all aircraft:

$$\min z = \sum_{k} \sum_{i,j} c_{ij} x_{ijk} \tag{19}$$

Here k is each individual aircraft, i is the location the aircraft is leaving, and j is the location to where the aircraft is going. The variable x is a 0 or 1 variable equal to 1 if the route is taken and 0 if it is not. The parameter c is a constant representing the distance or flight time between the locations. The aircraft capacity constraint is:

$$\sum_{i,j} \mu_i x_{ijk} \le Q \quad (k=1,\ldots,m) \tag{20}$$

Here m is the total number of aircraft and Q is the capacity of each aircraft, 48 in this case. The parameter $\mu_i$ is the probabilistic demand for location i. The final constraint simply states that the solution must be a member of the set of feasible solutions to the multiple traveling salesmen problem, $T_m$ (11:171).

$$x = (x_{ijk}) \in T_m \tag{21}$$

The suggested procedure is to determine routes based on a multiple traveling salesmen (MTSP) solution and then to heuristically fit the SVRP to this information. The MTSP is solved for the lower bound. If capacity restrictions are violated for one or more vehicles, locations are swapped between individual routes until capacity restrictions are met.

Merrill's MTSP formulation is used for those hubs with six or fewer servicing locations. Only Chicago and Atlanta have more than six locations to serve, 10 and 8 respectively. Here, other means will be necessary.

One of these means is utilizing a spacefilling curve (SFC) heuristic that Merrill successfully used to solve a single-based multi-aircraft traveling salesmen problem. As mentioned in the literature review, Bartholdi and Platzman suggest solving the VRP by first generating a SFC of the locations and then using a technique where the points closest together (and not violating the capacity constraints) are considered to be a route (3:296). The reason for attempting an approach such as this is because MAC's intentions are to develop a "soft" (somewhat flexible) schedule of flights for each hub. The spacefilling curve provides this flexibility.

Spacefilling curves are not just a two-dimensional tool. Bartholdi and Platzman also mention an example where Chauny et al. used a 3-dimensional version of their SFC algorithm to direct a machine as it cuts flat objects. The position on the object is the first two dimensions while the choice of cutting bit is the third dimension. The algorithm decides for the machine whether it is better to change bits and move to a closer position or to keep the same bit and move to a farther position (3:295-296). Other than this brief description, no other literature details 3-dimensional spacefilling curves.

This same idea can be applied to this MD80 problem. The third dimension would be the demands of the locations. The 3-dimensional SFC algorithm would then consist of three steps. First, utilizing the 3-dimensional spacefilling curve, for every location in a hub calculate a position on the unit interval (basically a mapping from 3 dimensions to a single dimension). The second step would consist of sorting the calculated positions. The final step would be to group the closest points into a number of sets equal to the number of aircraft allocated to that hub. Since aircraft capacity is directly linked to location demand, it follows that the resulting groups would be nearly the best probabilistic routes for the worst-case scenario.

This would provide most of the information desired by MAC. Allocation, shortfalls, and probabilistic routings have all been covered. Another goal of this research is to provide a real-time aircraft scheduling tool. Once again, the SFC with its speed in calculation could be the answer to this. The steps of the algorithm would change to reflect the deterministic demands. The final step would become a slight bit more complicated in that the total of the patients within groupings of locations would have to be less than or equal to 48. If this were not the case, swapping locations with the nearest grouping (obviously having less than 48 patients) would solve the problem.

The spacefilling curve is an important part of this research. A more thorough explanation of it follows.

## The Spacefilling Curve

The spacefilling curve is not a recent development. In fact, they were first described in 1890 as part of the family of fractal curves (3:291). A spacefilling curve is actually capable of mapping any dimension to any other. For this discussion only 2- and 3-dimensional mapping will be covered.

As the following figure shows, the curve is simply a line joining all the points within a space. The 2-

dimensional case is the easiest to explain. The square is divided into four quarters, each a square in itself. As the curve passes through each quarter it assigns the same value to all the points of interest in that quarter. In order to distinguish among points each quarter is broken into quarters allowing the curve to assign up to 16 different values.

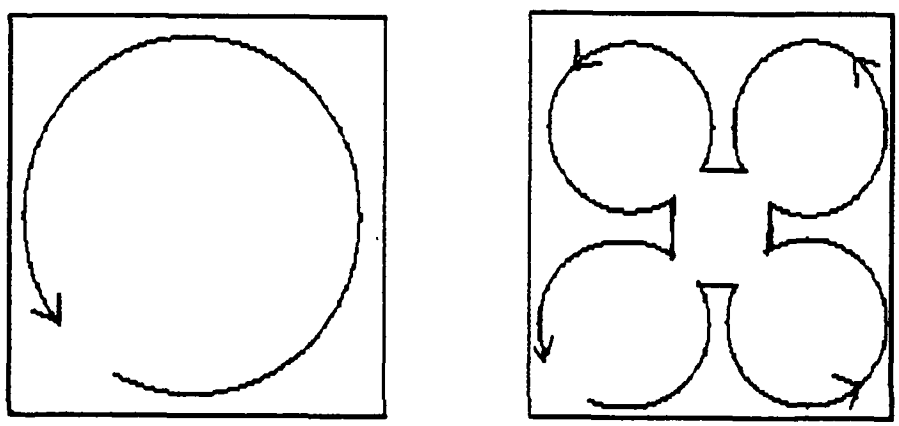


Figure 2: Spacefilling Curve

This process of individual squares breaking down into four more squares continues until each point of interest is assigned its own unique value on the curve. It follows that points close to each other in the square should then be close on the curve and indeed they are. The title "spacefilling curve" now seems logical since the line (curve) continues to fill the square until all points are "accounted for."

The 3-dimensional curve would operate much the same way except it would have 8 separate cubes to travel through.

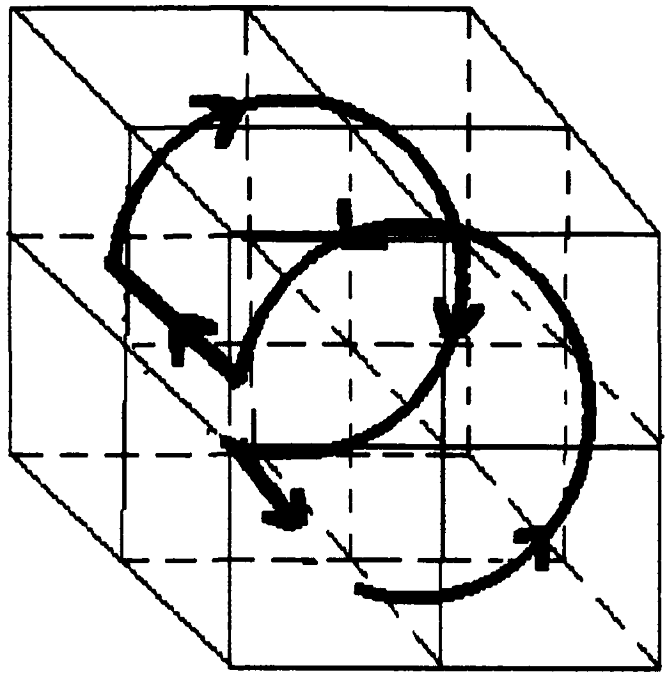


Figure 3: 3-Dimensional Spacefilling Curve

Once again, each of the 8 cubes is divided into 8 more cubes and "traveled" through. This process is continued until each point "owns" its own cube.

The spacefilling curve gives "good" answers, not 100% accurate answers. Bartholdi and Platzman claim as n (the number of points being considered) gets large, the curve will produce curves up to 25% longer than an optimal tour among the same points (3:295). Merrill found the curve to be within 4.5% of optimal on the average and no more than 10% overall (16:66). For aircraft traveling distances no greater than 500 miles, 10%, which equates to 10 minutes at 300 nautical miles per hour, is not much of a deviation to be of concern!

Finally, utilizing a spacefilling curve technique brings up the question of validation. Although the SFC has been proven relatively accurate in Merrill's work, his was a 2-dimensional example. No 3-dimensional SFC results have been documented. In order to prove its worth, its solutions must be compared to those found through the application of the previously mentioned math formulation. In this way, the validity of the 3-dimensional SFC can be determined.

## Assumptions

Several assumptions must be made to define the scope of the problem. These deal with aircraft, aircrews, hospitals, and patients.

It is assumed 30 MD-80 aircraft will always be available for the continental U.S. AES mission. Maintenance and downtime are not considered.

The MD-80 can carry any combination of different categories of patient as long as 48 or less are on board.

Ground times will be considered as one hour for servicing locations. This is the current scheduled ground time for MAC C-9s (1).

It is assumed all hospitals are standardized in their treatment of patients. Without this assumption it is impossible to use the "get well days" data.

Also, it is assumed the patients will be distributed to the hubs based on capability within category. For example, if there were only two hubs, and one hub could handle three patients in a specific category while the other hub could handle six in the same category, then the first hub would receive one-third of the patients in that category and the second hub two-thirds.

Since there are no mortality rates provided in the data, it is assumed all patients are alive and well after the prescribed number of recovery "get well days."

Finally, an assumption will be made that all patient categories are of equal importance. This limits having to preempt one category for another or determining degrees of injuries within a category.

The next chapter is the application of the methods developed here.

# Chapter IV: Results

## Allocation

Although not a large part of this thesis, allocation of the MD80 aircraft was the first priority of the Military Airlift Command's requests. It also was needed for the determination of aircraft routing.

As presented in the methodology, due to MAC's goal of distributing patients proportionally, allocation of patients was handled easily as a spreadsheet application. The procedure and the end result is displayed in Appendix C. The total patients distributed daily per hospital were then transferred to the "EXPECT" column of Appendix B.

The "EXPECT"-ed number of patients does no more than place an even patient load on each hospital, it does not tell what the hospital can actually handle on a daily basis. That is why the next step was to run a simulation model to ascertain whether an individual hospital could handle the expected load and, if not, what load it could handle. This was referred to in the methodology as a performance indicator.

The simulation was coded using the SLAM simulation language. A depiction of the SLAM network is presented in Figure 4. An example (Charleston S.C.) of the SLAM code is presented in Appendix F. The flow is quite simple. An aircraft arrives each day delivering patients in each category. Daily aircraft arrival is modelled using six

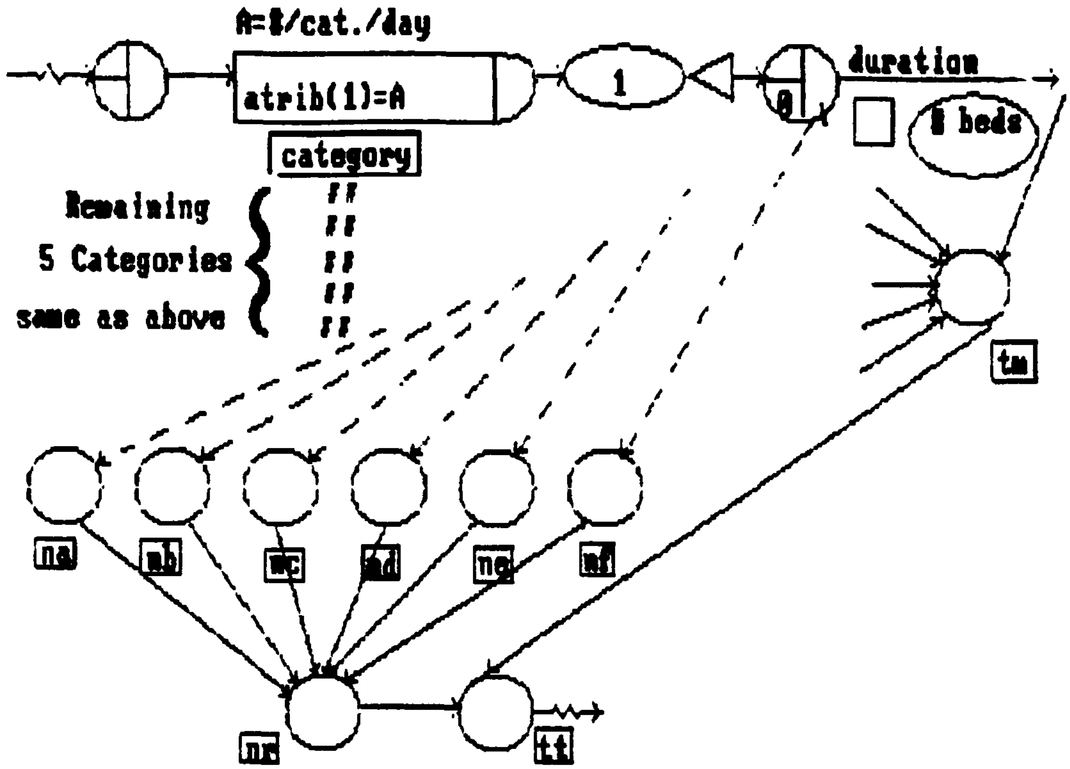



Figure 4: General SLAM Network

CREATE nodes. An attribute equal to the expected number of patients in the associated category is assigned to the arriving entity. An UNBATCH node then translates the aircraft entity into patient entities who immediately arrive at a zero-capacity queue. If beds are available (modelled with multiple service activities), the arriving patient is put to bed and started on his/her recovery. If no beds are available the patient balks and is counted as "not served" in that category. Totals for each category are added to produce a "total not served" value. Patients that arrive and find a bed are counted after their recovery. This is the "total served." The performance indicator is then calculated by the following equation.

$$\frac{\textit{total served}}{\textit{total served} + \textit{total not served}} = \textit{perf. ind.} \qquad (22)$$

An example of the SLAM output is presented in Appendix G.

Each hospital was simulated separately with this network. The performance indicators obtained in this fashion appear in the "percent probable" column of Appendix B. The "probable" column is simply the product of the "expect" column and the "percent probable" column. This final column is the number of patients each hospital should be able to handle each day.

Some of the larger hospitals exceeded the memory size limitations of SLAM. In order to determine their performance indicator each category of patient had to be simulated separately and the six sets of data aggregated manually to arrive at the single value desired (with a few of the largest hospitals it was necessary to break down the individual category in order to meet the memory size limitations).

With this done, allocation of aircraft seemed to be the next logical step. But here a question arose. Which number of patients, "expected" or "probable," is used to determine allocation? In the early stages of a conflict the hospitals will be able to handle the "expected" patient load. As the conflict progresses the hospitals will become saturated and can handle only the "probable" load. Therefore, the allocation of aircraft becomes a two-part process. This research refers to these as allocation for "unrestricted hospitals" and allocation for "restricted hospitals."

Allocation now becomes the simple process described in the methodology. These results follow.

Table II. Allocation of MD80 Aircraft

| Hub | # of Aircraft (unrestricted hospitals) | # of Aircraft (restricted hospitals) |
|---|---|---|
| Chicago | 6 | 4 |
| Atlanta | 4 | 3 |
| Houston | 4 | 3 |
| Philadelphia | 6 | 4 |
| Charlotte | 1 | 1 |
| Denver | 2 | 1 |
| Boston | 1 | 1 |
| Los Angeles | 1 | 1 |
| San Francisco | 2 | 1 |
| Total | 27 | 19 |

The total number is well below the 30 aircraft limit. Therefore, this conservative method suffices.

## Worst-Case-Average Routing

Before applying any algorithms it was necessary to determine the great circle distances as described in the methodology. Appendix A has the latitude and longitude of each point along with the x,y and z coordinate as determined using Equations (17). These coordinates were applied to Equation (18) to produce the distance matrices depicted in Appendix D.

Appendix E is the conversion of the values in Appendix

D to block hours. Just as a reminder, block hours are a more realistic depiction of travel time because it is the "gate to gate" travel time instead of just the flying time. Appendix F contains a tabular listing of the following discussion of routing results.

Unrestricted Hospital Routing. Two problems developed early when applying the math program to the times and patient loads. The first of these was the way the programs became explosively large with the addition of more nodes or aircraft. This was expected, though, and is the reason for the extensive research into the spacefilling curve as a heuristic procedure. An example of a math program used in this study is in Appendix H. The solution obtained with this program is in Appendix I. Due to this explosive nature of the math program the following discussion will depart from the past tradition of starting with the hub with the greatest number of nodes and ending with the hubs with the fewest nodes. Instead the hubs with the fewest nodes will be the first discussed.

The second problem existed with many of the patient loads. Some of them were well above the maximum aircraft capacity of 48. Without further complicating the math programming formulation with "frequency" constraints, a unique characteristic of vehicle routing problems allowed a solution to this dilemma.

The characteristic is termed by this author the "out-and-back" rule. Simply put, when a hospital's expected or probable patient load is greater than or equal to 48, an aircraft will be required to fly an "out-and-back" reducing the value of the patient load at that location by 48 each time. This is done until the value falls below 48. Once this rule is applied to all hospitals in a hub, the math program can be run. This is not a heuristic, just common sense. It can be proven correct for all possible cases.

As a simple example, suppose us say we are to route one plane from the Houston hub to San Antonio and Carswell AFB. Both have patient loads of 48. There are two possibilities. One would be to route the aircraft twice over the same route structure of San Antonio-Carswell-Houston. The second choice would be to apply the out-and-back rule and fly one out-and-back to each location. The total time required for the first option would be 3.92 block hours plus 5 hours ground time. The second option would only require 2.58 block hours plus 3 hours ground time, a savings of 3.34 hours! The logic is simple; there will always be a savings to be gained by taking full loads out-and-back if full loads exist.

The average worst-case routings for the Boston hub, Los Angeles hub and San Francisco hub are elementary. Each of these hubs service only two outlying hospitals. Boston only requires a single mission to Albany and back. This is because Northampton is inside the 100 mile minimum flying distance. Los Angeles requires two missions. Here the minimum time occurs when one mission flies out-and-back to Luke AFB and the second mission flies out-and-back to Tucson. Finally, San Francisco can be handled in much the same way. The minimum time occurs when one plane flies two out-and-back missions to Ft Lewis and another plane flies a single out-and-back to Portland.

Although the Charlotte hub has 4 outlying hospitals, Ft Bragg and Ft Jackson fall within the 100 mile minimum flying distance. This reduces Charlotte to the same route structure as Los Angeles. One out-and-back mission to each location, Charleston S.C. and Ft Gordon, is the minimum time.

Denver was the first hub where the math program described in the methodology was necessary. The previous hubs were determined by simple enumeration and the solutions verified with the math program. The minimum routing structure for Denver was to dedicate one plane to fly two out-and-back missions to Ft Bliss and have the second aircraft fly a "clean-up" mission via Hill AFB, Albuquerque, Ft Bliss, Wichita and Denver in that order. As a side note, this last route structure is also the optimal solution to the travelling salesman problem.

Philadelphia was the last hub the math program could be applied to before the formulation increased to a size beyond the limits of available software. The out-and-back rule coupled with the two mission a day per aircraft assumption required two aircraft to fly two out-and-backs each (4 total) to Washington DC. One aircraft would fly two out-and-backs to Norfolk. A fourth aircraft would fly one out-and-back to Norfolk and one out-and-back to Buffalo. A fifth aircraft would fly one out-and-back to Pittsburgh. The results of the math program suggested this aircraft fly a second out-and-back to Pittsburgh while the sixth aircraft flew one mission to Syracuse-Buffalo and a second mission to Washington DC-Norfolk.

The Houston hub actually formulated to a size suitable to fit into an available software package. The resulting answer had a subtour rendering it useless. The addition of subtour breaking constraints would have put the formulation out of limits for the software. The 3-dimensional spacefilling curve had to be turned to for the solution.

To this point all results were obtained either by enumeration backed up with a math program or by math program alone. As depicted in Appendix K, all these hubs were also attempted with the 3-dimensional spacefilling curve. This was intentionally done to provide a validation that the spacefilling curve could indeed give fairly accurate answers. Another item to note from Appendix K is that the full patient loads were input to the curve. In other words, the out-and-back rule was not used. This was a logical choice because the spacefilling curve does not "know" or reflect the aircraft's capacity. All the curve does "know" is where the nearest point is in the input space. The out-and-back rule was unnecessary. The code for the 3-dimensional (and 2-dimensional) SFC is presented in Appendix J. The programming language is BASIC. Before proceeding with the remaining routing results, a short explanation of the BASIC program is necessary.

The BASIC program simply assigns a value, theta, to each location. This value is a number between 0 and 1 (the unit interval). Theta represents how far on this unit length curve one must travel to get to that location. Besides entering the three "dimensional" variables, the program also requires that a k-value be entered. What k tells the program is how many times to break down the cube. For instance, a k-value of 1 would result in the initial cube being broken down into 8 smaller cubes. A k-value of 2 would cause 64 total cubes (8 separate cubes each broken down into 8 more cubes). The resulting number of cubes within the original cube is equal to $8^k$. The object is to find the minimum value for k that assigns each location a unique value. Each of the cubes after the dividing process contains a unique value. Therefore, if you have 20 locations to separate out on the curve, you need to use a k-value of at least 2 because a value of 1 would only give 8 different values, at most.

This same discussion applies to the 2-dimensional case.

Here, $4^k$ is the important value to consider.

In either case, the object is still to use the least k-value possible. This is because higher values of k will cause the addition of relative "distance" within the initial cube. This would serve only to distort the theta values for each location.

As an example of the spacefilling curve's accuracy, consider the Philadelphia hub. The following output from the curve was generated:

Table III. 3-Dimensional Spacefilling Curve Results For the Philadelphia Hub

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | NORFOLK | 36.895 | 76.2 | 149 | .328125 |
| 2 | PHILADELPHIA | 39.87 | 75.245 | 0 | .375 |
| 3 | WASHINGTON DC | 38.487 | 76.52 | 212 | .75 |
| 4 | PITTSBURGH | 40.492 | 80.232 | 93 | .796875 |
| 5 | BUFFALO | 42.94 | 78.733 | 83 | .921875 |
| 6 | SYRACUSE | 43.11 | 76.103 | 13 | .953125 |

To interpret these results only requires looking for points nearest each other and occasionally considering the 48 patient capacity. At first glance, it is obvious Norfolk, Washington DC, Pittsburgh and Buffalo will require a certain number of out and backs. This is where the rule is finally applied. After the out and backs are determined, Norfolk is left with 5 patients, Washington DC with 20, Pittsburgh with 45 and Buffalo with 35. The two locations closest on the curve are Buffalo and Syracuse. The sum of their patient loads equates to 48 (not that the curve knew this!).

Although Washington DC and Pittsburgh are the next closest points, their remaining patients exceed 48. The next nearest two points are Washington DC and Norfolk whose loads add to 25. Pittsburgh is left on its own. As can be seen, this is the same result obtained by the math program earlier in this chapter. A similar comparison was made with the remaining 5 hubs. In all cases the curve emulated the math program exactly. This is significant because in all cases the spacefilling curve program ran for a fraction of the time it took to run the math program. As the number of nodes increased, this significance became even more pronounced. Therefore, this not only validates the use of the spacefilling curve but also shows its strength as a routing tool. Appendix K contains all the spacefilling curve results and graphical representations of the larger hubs (the graphical representations help to visualize the closeness among certain points).

To continue with the routing results, Houston now became a tractable problem. Applying the spacefilling curve yielded an out-and-back to San Antonio, one to Carswell AFB and three to New Orleans. Another mission would fly to San Antonio-Carswell AFB, while yet another flew New Orleans-Shreveport. Two more missions would fly out-and-back to Oklahoma City and to Little Rock AFB. This would require nine missions and five aircraft.

Another strength of the spacefilling curve appeared during the Houston hub problem. Note that five aircraft were required instead of the four found during allocation. This suggested a split delivery would reduce the aircraft needed to four. Even applying a math program (that does not allow split deliveries) would result in requiring nine missions and five aircraft. The procedure for checking for split deliveries adds some complication to the previous spacefilling curve method but is still quicker and easier than incorporating split deliveries into a math program.

The procedure requires starting at the hub on the curve and proceeding to the next closest point, Shreveport in this case. This keys Shreveport as the split delivery location. Obviously, it should split its delivery with the two closest points not including the hub. These are Oklahoma City and Little Rock AFB. Splitting Shreveport with these locations eliminates the two out-and-back legs each to Oklahoma City and Little Rock AFB and replaces them with one mission, Shreveport-Oklahoma City. The previous New Orleans-Shreveport mission now adds Little Rock AFB to make that mission New Orleans-Shreveport-Little Rock AFB. Notice that the curve even suggests the optimal routing within the mission. This same procedure was tested with several "made-up" problems at other hubs. Houston was the only hub in this thesis that actually benefitted from this procedure.

Atlanta required little effort to determine the routes for its four aircraft. They were out-and-backs to Orlando, Jacksonville, Birmingham, Nashville, Knoxville and Jackson. The remaining aircraft would fly Homestead-Orlando-Jacksonville and Nashville-Millington (Memphis).

The final hub is the largest hub, Chicago. Wright-Patterson AFB and Scott AFB both required two out-and-backs each. Lexington and Allen Park (Detroit) required one out-and-back each. The curve suggested flying out-and-backs to Offutt AFB, Cleveland and Ft Leavenworth. One mission would fly Lexington-Wright-Patterson AFB, while another would go Minneapolis-Allen Park. A final mission would fly Indianapolis-Des Moines-Scott AFB. As with Atlanta, no split deliveries would be necessary because it would be impossible to reduce the number of aircraft loads to below twelve (Atlanta to below eight).

Restricted Hospital Routing. The above mentioned procedure was then applied in the same fashion to the probable patient loads. As a review, these are the hospital loads expected once the hospitals are near saturation.

Boston, Los Angeles and San Francisco reduce to requiring only one aircraft each. Boston and Los Angeles would only need one mission a day to delivery all their patients. San Francisco would require two missions, one out-and-back to Ft Lewis and then a Portland-Ft Lewis mission.

Charlotte would require a single Charleston-Ft Gordon mission.

Denver's route structure, as compared to the previous Denver structure, would differ only by one out-and-back to Ft Bliss. Under the probable patient loads only one instead of two out-and-backs to Ft Bliss would be necessary.

Philadelphia reduces to all out-and-backs and one mission covering all locations. Washington would require three out-and-backs, Norfolk would require two, Pittsburgh and Buffalo would each require one. The math program suggests a final mission would fly the optimal travelling salesman route of Syracuse-Buffalo-Pittsburgh-Washington DC-Norfolk. This was the only noted failure of the 3-dimensional SFC because it suggests a route where Syracuse would end the mission instead of Norfolk.

The spacefilling curve results in Appendix L were needed once again to solve the routes for the remaining hubs. As with Appendix K, Appendix L contains both the spacefilling curve results and a graphical representation of the larger hubs.

Houston routes were comprised of two out-and-backs to New Orleans and one out-and-back to San Antonio. Other missions would be Carswell AFB-New Orleans and Shreveport-Little Rock AFB-Oklahoma City. As before, the spacefilling curve verifies all the previous answers except for the one deviation with Philadelphia.

With Atlanta, the minimum routing via spacefilling curve required single out-and-backs to Orlando, Jacksonville and Nashville. Remaining routes were Millington-Jackson, Homestead AFB-Birmingham and Knoxville-Jacksonville-Orlando.

After out-and-backs to Scott AFB, Lexington, Allen Park and Wright-Patterson AFB, Chicago's route structure reduced to missions of Des Moines-Offutt AFB-Ft Leavenworth, Indianapolis-Wright Patterson AFB and Cleveland-Minneapolis.

## Spacefilling Curves as Routing Tools

The previous discussion of average routing shows the power of the spacefilling curve. The intentions of this thesis were to not only use this heuristic method for average route determination but also to determine its strength as a day to day routing tool.

The 2-Dimensional SFC Heuristic. Bartholdi and Platzman discuss one possible way of doing this with a 2-dimensional SFC (3:296). Their suggestion was to group the demands of locations together keeping close attention to aircraft capacity. In Appendix M the author has attempted this procedure by enhancing the 2-dimensional SFC results with a graph depicting the SFC results on the x axis and demand on the y axis. This has been done for the hubs with more than two outlying hospitals to service. The demands were obtained by taking the expected patient numbers in Appendix B and subtracting out multiples of 48 from the numbers over 48. For this discussion, Philadelphia will be used as an example of the 2-dimensional routing procedure.

The following figure is extracted from Appendix M. It is the result of the SFC results plotted against the location demands.

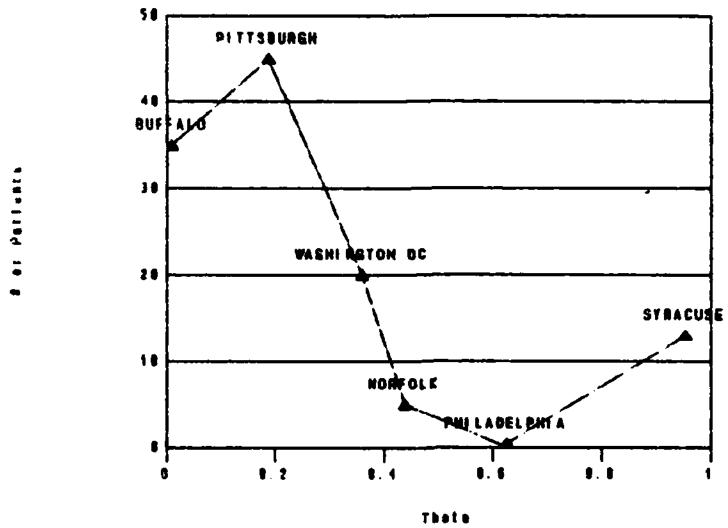



Figure 5: 2-D SFC Philadelphia Results

The first step is to eliminate those locations that do not match up with any other location to produce a vehicle capacity less than 48. For this example, Pittsburgh is assigned as a single route for aircraft #1. The next step is to combine locations that are close and add to less than 48. Washington DC and Norfolk are an example of this. Their's becomes the #2 route. Syracuse could easily be added to the #2 route without exceeding the capacity of 48 but Syracuse can also be added to Buffalo to produce a full 48 patient load. Which is a better choice? Obviously Syracuse should be placed with the locations it is closer to. Although the graphical depiction places Buffalo and

Syracuse at opposite ends of the unit interval, a property of the SFC is its continuity. A location with a theta value of 1 is identical to a location with a theta value of 0. A theta value of 0.5 is actually the farthest point from 0. For this example, Syracuse should be placed with Buffalo because it is closer to Buffalo than to either Washington DC or Norfolk. Thus the #3 route would be Syracuse-Buffalo.

For all the hubs, using them as test cases, this procedure came up with the same answers as the math program (except for Chicago, Atlanta, and Houston since they could not be solved by means of a math program).

<u>The 3-Dimensional SFC Heuristic</u>. It is the nature of man to always look for a "shorter" or "easier" way to do things. Although not mentioned in any literature, this author believed the 3-Dimensional SFC could be a quicker means of arriving at a vehicle routing decision. Appendix N contains the results when the expected patients were used and Appendix O contains the results when the probable patients were used.

Once again Philadelphia will be used as an example. The following figure was extracted from Appendix N. The axes are the same as in the 2 dimensional cases but this time the "# of Patients" axis is for information only. This is because the patient number is already included in the theta value. This "# of Patients" axis is only needed for occasional vehicle capacity limit reasons since the curve cannot determine capacity.

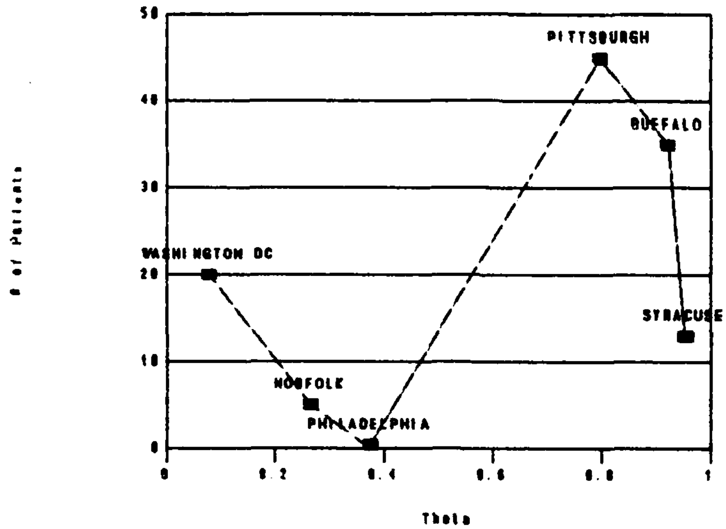



Figure 6:  3-D SFC Philadelphia Results

This time the routing decision is easier.  Buffalo and Syracuse are bunched together.  Pittsburgh seems to stand by itself.  Washington DC and Norfolk, although not noticeably "close," are still closer to each other than they are to any other locations.

Once again, the answers in appendices N and O match those from the math program solutions.

Overall, the only time the spacefilling curve (3-dimensional) differed from math program results was in the one instance with the Philadelphia Hub during restricted hospital routing.  Taking this into account for the nine separate hubs added together, amounted to a difference of 1.69% (greater) from the overall off-station times obtained from the math program as compared to the 3-dimensional spacefilling curve. This, again, was only in the case of the restricted hospital routing. For unrestricted routing and all tests of the spacefilling curve as a routing tool, the results were the same as the results obtained with the math program.

## Chapter V: Analysis of Results

This section will conclude the thesis by discussing some of the accomplishments of this work along with some of the failures. It will follow in the same order that has prevailed throughout the paper; allocation, worst-case-average routing and day to day scheduling.

### Allocation

Allocation turned out to be an easily obtainable set of answers. Since the results came well below the upper limit of 30 MD80 aircraft, some of the harshly conservative assumptions proved palatable. This is directly referring to the two missions per day per aircraft assumption which was derived from the conservative 10 hour maximum off station aircraft limit assumption. Both of these assumptions could be relaxed to provide an even fewer number of required aircraft. An example of this would be the Philadelphia hub network. Appendix P shows two aircraft being dedicated to Washington DC alone. Each of these missions is only 1.68 hours in length. If the two mission per day limit were relaxed these four missions could easily be handled by one aircraft. Similar situations occur at other hubs.

In order to find a more realistic minimum number of MD80s required per hub, the following equation was utilized, rounding up to the nearest integer. This equation had the advantage of being based on the minimum spanning tree approximation to the traveling salesman problem. Here, "block hours" pertained to those flying hours required to establish an upper bound on the flying hours. This was obtained by considering all the routes to be out-and-backs to the respective outlying hospitals. "Duty hours" referred to the 10 hour maximum crew off-station time. "Capacity" was the 48 total patients per aircraft and "Patient #s" was the total number delivered each day.

$$\#\ of\ MD80s = \frac{(Block\ hours)\ (Patient\ \#s)}{(duty\ hours)\ (Capacity)\ (24\ hours)} \tag{23}$$

Using this equation resulted in the following table of values:

Table IV. Revised Allocation of MD80 Aircraft

| Hub | # of Aircraft (unrestricted hospitals) | # of Aircraft (restricted hospitals) |
|---|---|---|
| Chicago | 5 | 3 |
| Atlanta | 4 | 3 |
| Houston | 4 | 3 |
| Philadelphia | 5 | 3 |
| Charlotte | 1 | 1 |
| Denver | 2 | 1 |
| Boston | 1 | 1 |
| Los Angeles | 1 | 1 |
| San Francisco | 1 | 1 |
| Total | 24 | 17 |

This suggests if for some reason in the future the Civil Air Reserve Fleet is unable to provide all 30 MD80s, 24 would be the minimum number of aircraft needed to sustain operations.

The 10 maximum off station limit is also quite conservative and, in fact, was violated once in the results. This occurred with the Denver network. The clean-up mission is scheduled for 10.33 hours, missing the assumed constraint of 10 hours by 0.33 hours. It must be realized that this 10 hour maximum was based on the aircraft operating with an inoperative auto pilot. Fourteen hours would be the limit if normal operations were assumed. From this author's experience as an Air Force pilot of transport aircraft, auto pilot failures are extremely rare in Air Force transports. It seems logical that if civilian aircraft in-service rates are greater than those of the Air Force's, their failures are even more rare. Relaxation of this assumption (as this thesis did on one occasion) would lessen the number of required aircraft even more.

With these ideas in mind, a suggestion would be to eliminate any aircraft from being allocated to the Boston hub. Boston's only outlying hospital, Albany, only requires one mission per day, and a short one at that. Philadelphia is the nearest hub to Boston. Two possibilities exist. The first would be to assign Albany to Philadelphia for service. The second would be to direct a mission from Philadelphia to Boston to pick up patients for Albany, deliver them and return to Philadelphia.

Another finding that surfaced during the allocation process was the discovery of shortfalls in the number of beds in certain categories. The simulations performed in this thesis found in all cases the number of burn injury beds (SB), surgical medical beds (SS) and orthopedic beds (SO) were lacking. These were the categories that causes the requirement of a "probable" number of patients for each hospital. The only foreseeable solution is to bring more hospitals into the NDMS system.

To finalize this section on allocation, if in the future it becomes necessary to re-determine the hubs and associated servicing hospitals, the spacefilling curve could easily be employed here also. Re-optimization of hubs and service locations would affect both allocation and routing. Bartholdi and Platzman suggest the SFC can solve partitioning problems such as this. They suggest running the SFC program, divide the interval into a desired number of subintervals (identical), and then choose the medians to be the points nearest the center of these intervals (3:296-298).

A look at appendix Q shows a listing of all 52 locations separated out on the unit interval. By applying their suggested algorithm, you can roughly see a strong resemblance to the present hub and spoke system. A recommended follow on to this thesis effort would be to scout this avenue for further improvements to the current hub and spoke system.

## Worst-Case-Average Routing

The purpose of providing an average worst-case routing was made clear in the introduction. In order for Military Airlift Command to put together a viable Operations Plan (OPLAN) or even an operational plan in concept format (CONPLAN) for aeromedical evacuation, it is necessary to apportion the available assets and at least roughly portray the use of those assets. Therefore, besides allocating the Civil Reserve Air Fleet MD80s, it was necessary to determine the most likely routes they would fly.

It was obvious that in the beginning of an execution of such an OPLAN or CONPLAN the hospitals would be able to take their equal share of the proposed incoming patients. As the conflict progressed, these hospitals would lose their ability to handle their share, thus decreasing the need for airlift from hub to outlying hospital. The question then arises whether or not these suggested routes (Appendix P) are indeed the "worst-case-average"?

In a paralleling thesis effort Captain Michael Burnes did a deterministic 90 day routing study on a day by day basis. Each day of the conflict he would take the expected number of arriving patients (4440, the same as this thesis) and equally distribute them among all the hospitals providing beds were available. He would then use the well-proven Clarke-Wright vehicle routing algorithm to route the aircraft based on the daily patient loads (5).

This parallel effort provided a validation for the average routing proposed in this thesis. A comparison was made between his total 90 day aircraft off station hours and this author's total restricted hospital off station hours multiplied times 90.

There was one assumption made by Captain Burnes that was not considered in this thesis. He assumed, due to the large number of general medical (MM) and psychological (MP) beds available at the hubs themselves, he would not distribute these patients evenly among all hospitals, hub and outlying, but instead would assign them beds within the hub itself (5).

To bring this thesis effort into line with his in order to make the comparison, it was necessary to eliminate distributing patients in the categories of MM and MP. A glance at appendix G (a sample SLAM simulation output) shows the ease in which this was done. By taking the total number of patients served in the MM and MP categories (Queues 1 and 2 entity counts) and subtracting it from both the total number of entities and the total served then dividing the new total served by the new total number of entities would give that hospitals new "percent probable" value. Using appendix G as an example would give a new "percent probable" value for Charleston S.C. as 0.503, a decrease from the original 0.571 value.

Using these new values it was a simple multiplication to create new probable patient loads (all lesser than previous). Due to time limitations on the completion of this thesis the 3 dimensional spacefilling curve (because of its overwhelming speed and previously proven accuracy for these size networks) was the only technique used to determine the new routes for comparison. The off station hours were then added up and multiplied by 90 days (per hub) to complete the comparison. The following table shows the final results.

Table V. 90 Day Off Station Route Hours
Comparison Between Deterministic and Stochastic
Route Determinations

| Hub | Deterministic (hours) | Stochastic (hours) | Percent Difference |
|---|---|---|---|
| Chicago | 1933 | 1972.32 | 2.03 |
| Atlanta | 1642 | 1736.91 | 5.78 |
| Houston | 1269 | 1333.68 | 5.10 |
| Philadelphia | 1165 | 1183.64 | 1.60 |
| Charlotte | 222 | 243.46 | 9.67 |
| Denver | 882 | 954.34 | 8.20 |
| Boston | 135 | 150.69 | 11.41 |
| Los Angeles | 296 | 319.38 | 7.89 |
| San Francisco | 544 | 580.45 | 6.70 |
| Totals | 8088 | 8474.87 | 4.78% |

These results are sufficient evidence that the average routing is indeed correct. The 4.78 percent overall difference is negligible. Also notice that in this comparison, those hubs with larger numbers of patients to transport (Chicago and Philadelphia) also have the smaller differences. This is because these hubs had outlying hospitals with more capability. For the hubs with lesser capable outlying hospitals, Captain Burnes would refuse to fly a single patient to a certain hospital if another hospital with a greater load could absorb that single patient (5). The SFC technique delivers the patient regardless of other hospital capabilities thus keeping in line with the "even distribution" rule imposed by MAC.

Another interesting comparison between the two efforts is the average time a bed is available. This serves to validate the SLAM results. For example, he was able, through his accounting methods, to determine how long a specific category bed was empty over the 90 day period. This would equate to taking the "average util" (average utilization per category) in appendix G (Example SLAM Output), dividing it by the "ser cap" (server capacity or number of servers in that category), and then subtracting the result from one. This would give the average amount of time a bed was idle for the simulation. Doing this with the remaining 42 outlying hospitals and combining the results per category would give a value to compare with his.

It was found in all categories the numbers compared favorably. For example, Captain Burnes found that 15% of the time an SO bed was available. The SLAM results found that 14.86% of the time an SO bed was available. For the remaining categories the differences were just as insignificant. Therefore, the SLAM results can be considered valid.

## Spacefilling Curves as a Routing Tool

The final goal of this thesis was to present a possible means of determining routes once the patients inbound to a specific hub become available. Math programs, although providing the most accurate answers, are not the most user friendly or portable (meaning hardware compatibility). The spacefilling curve heuristic, on the other hand, is a simple BASIC program (appendix J). BASIC is available or compatible with most hardware configurations. This makes the SFC both user friendly and portable. As this thesis has proven, the SFC gives "good" answers especially for the size networks involved here. Both the 2-dimensional and 3-dimensional curves are good tools. This author believes less interpretation is required for the 3-dimensional case, making it the better choice. It would be much easier to explain and teach the interpretation of the spacefilling curve output to a flight scheduler than it would be to explain and teach the ins and outs of a math program.

Finally, the issue of the spacefilling curve heuristic as a better tool than a standard vehicle routing algorithm would not be complete without a short discussion of complexity theory. According to Bartholdi and Platzman, the SFC heuristic is a $O(n \log n)$ heuristic with an error of $O(\log n)$ (3:295). A standard vehicle routing algorithm such as the Clarke-Wright is an $O(n^3)$ method (3:296). This does not say the SFC is any better, it claims that it is faster.

For large applications where time is important, the SFC could render a "good" answer quickly. This is important in the operational arena where personnel are not appreciative of long waiting periods even if the answer is "optimal." Speed and "near" efficiency is what is appreciated. Thus the argument tends to favor the spacefilling curve. (An expert system utilizing a Clarke-Wright algorithm, rule reduced by a spacefilling curve, is provided in Appendix R.)

## Recommendations

To summarize the efforts of this thesis this author recommends the allocation of aircraft as per Table II. Appendix P lists the routes that could be termed the most likely. For OPLAN or CONPLAN purposes, the first column of routes (Unrestricted Hospitals) would provide the most capability early on in a conflict. Finally, as a real time routing tool, the 3-dimensional spacefilling curve heuristic provides the quickest and easiest to interpret information for determining routes. It is easy to run the program which could be installed on any hardware available (especially at Air Force wing or squadron levels).

Hopefully, this effort has provided a good "first cut" at shaping the future plans for enhancing the aeromedical evacuation system. As more detailed data on patients, hospitals, and aircraft become available, a more directed and complete analysis can be accomplished with this effort as a launching point.

## Appendix A: NDMS Hospital Locations Based on Servicing Airport

| Hospital | Airport | Latitude | Longitude | X | Y | Z |
|---|---|---|---|---|---|---|
| ALBANY | KALB | 42.650 | 73.750 | 708.48 | 2429.82 | 2331.20 |
| ALBUQUERQUE | KABQ | 35.025 | 106.364 | -793.55 | 2703.89 | 1974.78 |
| ALLEN PARK | KDTW | 42.215 | 83.348 | 295.50 | 2531.44 | 2311.92 |
| ATLANTA | KATL | 33.640 | 84.427 | 278.52 | 2851.26 | 1906.10 |
| BIRMINGHAM | KBHM | 33.563 | 86.755 | 162.63 | 2862.78 | 1902.25 |
| BOSTON | KBOS | 42.363 | 71.007 | 827.73 | 2404.15 | 2318.49 |
| BUFFALO | KBUF | 42.940 | 78.733 | 492.45 | 2470.57 | 2343.98 |
| CARSWELL AFB | KFWH | 32.461 | 97.265 | -366.81 | 2880.18 | 1846.75 |
| CHARLESTON SC | KCHS | 32.898 | 80.040 | 500.02 | 2845.68 | 1868.84 |
| CHARLOTTE | KCLT | 35.213 | 80.943 | 442.86 | 2776.34 | 1984.01 |
| CHICAGO | KORD | 41.980 | 87.905 | 93.80 | 2556.37 | 2301.45 |
| CLEVELAND | KCLE | 41.412 | 81.850 | 366.13 | 2554.67 | 2275.98 |
| DENVER | KBKF | 39.426 | 104.455 | -663.17 | 2574.04 | 2185.18 |
| DES MOINES | KDSM | 41.535 | 93.660 | -164.12 | 2570.65 | 2281.51 |
| FT BLISS | KBIF | 31.850 | 106.380 | -823.91 | 2804.45 | 1815.69 |
| FT BRAGG | KPOB | 35.170 | 79.015 | 536.29 | 2761.33 | 1981.90 |
| FT GORDON | KAGS | 33.370 | 81.965 | 401.99 | 2845.53 | 1892.58 |
| FT JACKSON | KCAE | 33.940 | 81.120 | 440.98 | 2820.55 | 1921.07 |
| FT LEAVENWORTH | KMCI | 39.298 | 94.725 | -219.03 | 2653.95 | 2179.24 |
| FT LEWIS | KGRF | 47.083 | 122.578 | -1261.41 | 1974.77 | 2519.84 |
| HILL AFB | KHIF | 41.076 | 111.583 | -953.88 | 2412.33 | 2260.80 |
| HOMESTEAD AFB | KHST | 25.293 | 80.230 | 528.26 | 3066.00 | 1470.06 |
| HOUSTON | KEFD | 29.364 | 95.095 | -265.97 | 2987.15 | 1687.20 |
| INDIANAPOLIS | KIND | 39.725 | 86.283 | 171.87 | 2641.07 | 2199.02 |
| JACKSON | KJAN | 32.312 | 90.077 | -3.57 | 2908.24 | 1839.19 |
| JACKSONVILLE | KJAX | 30.493 | 81.690 | 428.86 | 2933.97 | 1745.96 |
| KNOXVILLE | KTSY | 35.812 | 83.993 | 292.33 | 2775.19 | 2013.30 |
| LEXINGTON | KLEX | 38.037 | 84.605 | 255.12 | 2698.25 | 2120.11 |
| LITTLE ROCK AFB | KLRF | 34.550 | 92.088 | -102.93 | 2832.33 | 1951.35 |
| LOS ANGELES | KLAX | 33.942 | 118.407 | -1357.71 | 2511.22 | 1921.17 |
| LUKE AFB | KLUF | 33.321 | 112.229 | -1087.41 | 2661.86 | 1890.12 |
| MILLINGTON | KNQA | 35.355 | 89.870 | 6.69 | 2806.50 | 1990.98 |
| MINNEAPOLIS | KMSP | 44.885 | 93.215 | -136.45 | 2434.35 | 2428.13 |
| NASHVILLE | KBNA | 36.127 | 86.682 | 161.18 | 2774.75 | 2028.61 |
| NEW ORLEANS | KMSY | 29.992 | 90.252 | -12.76 | 2980.27 | 1719.97 |
| NORFOLK | KORF | 36.895 | 76.200 | 656.70 | 2672.49 | 2065.68 |
| NORTHAMPTON | KCEF | 42.118 | 72.318 | 775.52 | 2431.88 | 2307.60 |
| OFFUTT AFB | KOFF | 41.071 | 95.547 | -250.45 | 2582.16 | 2260.58 |
| OKLAHOMA CITY | KOKC | 35.251 | 97.233 | -353.46 | 2787.80 | 1985.88 |
| ORLANDO | KMCO | 28.428 | 81.317 | 457.16 | 2991.40 | 1637.99 |
| PHILADELPHIA | KPHL | 39.870 | 75.245 | 672.89 | 2553.93 | 2205.71 |
| PITTSBURGH | KPIT | 40.492 | 80.232 | 444.26 | 2579.00 | 2234.25 |
| PORTLAND | KPDX | 45.588 | 122.597 | -1297.04 | 2029.07 | 2457.86 |
| SAN ANTONIO | KSKF | 29.228 | 98.350 | -435.71 | 2971.19 | 1680.08 |

| Hospital | Airport | Latitude | Longitude | X | Y | Z |
|---|---|---|---|---|---|---|
| SAN FRANCISCO | KSFO | 37.618 | 122.373 | -1459.06 | 2302.31 | 2100.23 |
| SCOTT AFB | KBLV | 38.326 | 89.511 | 23.35 | 2699.45 | 2133.75 |
| SHREVEPORT | KBAD | 32.301 | 93.398 | -172.05 | 2903.50 | 1838.64 |
| SYRACUSE | KSYR | 43.110 | 76.103 | 603.61 | 2438.61 | 2351.44 |
| TUCSON | KDMA | 32.099 | 110.529 | -1021.87 | 2730.08 | 1828.37 |
| WASHINGTON DC | KADW | 38.487 | 76.520 | 628.14 | 2619.28 | 2141.33 |
| WICHITA | KIAB | 37.374 | 97.160 | -340.51 | 2713.35 | 2088.61 |
| WRIGHT-PATT AFB | KFFO | 39.496 | 84.029 | 276.52 | 2640.99 | 2188.42 |

# Appendix B: Hospital Patient Data Including Expected Daily Demand For Beds And Probability That The Hospital Can Handle The Demand

| HOSPITAL | MM | MP | SS | SO | SC | SB | TOTAL | EXPECT | PERCENT PROBABLE | PROBABLE |
|---|---|---|---|---|---|---|---|---|---|---|
| HUB = CHICAGO | | | | | | | | | | |
| ALLEN PARK | 592 | 154 | 514 | 130 | 29 | 26 | 1445 | 61 | 0.699 | 43 |
| CHICAGO | 2204 | 568 | 2651 | 547 | 88 | 95 | 6153 | 271 | ----- | -- |
| CLEVELAND | 344 | 197 | 287 | 103 | 41 | 33 | 1005 | 42 | 0.687 | 29 |
| DES MOINES | 65 | 27 | 84 | 12 | 4 | 3 | 195 | 8 | 0.606 | 5 |
| FT LEAVENWORTH | 222 | 76 | 382 | 84 | 24 | 6 | 794 | 37 | 0.565 | 21 |
| INDIANAPOLIS | 250 | 77 | 84 | 33 | 8 | 3 | 455 | 17 | 0.540 | 9 |
| LEXINGTON | 261 | 92 | 395 | 192 | 5 | 1 | 946 | 55 | 0.634 | 35 |
| MINNEAPOLIS | 88 | 149 | 338 | 73 | 27 | 11 | 686 | 34 | 0.535 | 18 |
| OFFUTT AFB | 583 | 104 | 126 | 178 | 14 | 16 | 1021 | 43 | 0.411 | 18 |
| SCOTT AFB | 665 | 130 | 1216 | 276 | 0 | 0 | 2287 | 119 | 0.689 | 82 |
| WRIGHT-PATT AFB | 537 | 155 | 880 | 318 | 120 | 96 | 2106 | 113 | 0.731 | 83 |
| HUB = ATLANTA | | | | | | | | | | |
| ATLANTA | 706 | 84 | 467 | 309 | 3 | 35 | 1604 | 84 | ----- | -- |
| BIRMINGHAM | 514 | 71 | 487 | 56 | 12 | 9 | 1149 | 45 | 0.650 | 29 |
| HOMESTEAD AFB | 60 | 27 | 82 | 0 | 3 | 0 | 172 | 7 | 0.737 | 5 |
| JACKSON | 336 | 166 | 315 | 23 | 16 | 8 | 864 | 29 | 0.701 | 20 |
| JACKSONVILLE | 456 | 193 | 393 | 355 | 54 | 57 | 1508 | 86 | 0.743 | 64 |
| KNOXVILLE | 206 | 57 | 209 | 64 | 9 | 1 | 546 | 25 | 0.542 | 14 |
| MILLINGTON | 427 | 160 | 248 | 59 | 25 | 4 | 923 | 31 | 0.612 | 19 |
| NASHVILLE | 468 | 199 | 490 | 161 | 13 | 5 | 1336 | 59 | 0.609 | 36 |
| ORLANDO | 875 | 154 | 702 | 201 | 57 | 50 | 2039 | 86 | 0.765 | 66 |
| HUB = HOUSTON | | | | | | | | | | |
| CARSWELL AFB | 683 | 147 | 502 | 174 | 52 | 0 | 1558 | 65 | 0.494 | 32 |
| HOUSTON | 1211 | 246 | 1205 | 402 | 5 | 26 | 3095 | 146 | ----- | -- |
| LITTLE ROCK AFB | 80 | 10 | 83 | 86 | 0 | 0 | 259 | 18 | 0.327 | 6 |
| NEW ORLEANS | 2323 | 635 | 1271 | 325 | 79 | 23 | 4656 | 161 | 0.652 | 105 |
| OKLAHOMA CITY | 227 | 52 | 422 | 120 | 1 | 0 | 822 | 44 | 0.526 | 23 |
| SAN ANTONIO | 1150 | 291 | 428 | 138 | 9 | 35 | 2051 | 66 | 0.732 | 48 |
| SHREVEPORT | 229 | 101 | 106 | 32 | 0 | 4 | 472 | 15 | 0.586 | 9 |

| HOSPITAL | MM | MP | SS | SO | SC | SB | TOTAL | EXPECT | PERCENT PROBABLE | PROBABLE |
|---|---|---|---|---|---|---|---|---|---|---|
| HUB = PHILADELPHIA | | | | | | | | | | |
| BUFFALO | 813 | 128 | 671 | 202 | 25 | 17 | 1856 | 83 | 0.610 | 51 |
| NORFOLK | 1201 | 516 | 1061 | 434 | 22 | 46 | 3280 | 149 | 0.724 | 108 |
| PHILADELPHIA | 4209 | 1286 | 3367 | 784 | 228 | 102 | 9976 | 384 | ----- | -- |
| PITTSBURGH | 1366 | 110 | 946 | 134 | 30 | 10 | 2596 | 93 | 0.676 | 63 |
| SYRACUSE | 219 | 31 | 47 | 16 | 4 | 38 | 355 | 13 | 0.633 | 8 |
| WASHINGTON DC | 1604 | 357 | 1403 | 711 | 170 | 23 | 4268 | 212 | 0.711 | 151 |
| HUB = CHARLOTTE | | | | | | | | | | |
| CHARLESTON SC | 212 | 78 | 277 | 62 | 3 | 12 | 644 | 29 | 0.571 | 17 |
| CHARLOTTE | 527 | 344 | 370 | 102 | 41 | 14 | 1398 | 48 | ----- | -- |
| FT BRAGG | 1621 | 533 | 1632 | 714 | 142 | 135 | 4777 | 234 | 0.693 | 161 |
| FT GORDON | 274 | 212 | 169 | 150 | 29 | 14 | 848 | 39 | 0.430 | 17 |
| FT JACKSON | 420 | 110 | 242 | 149 | 24 | 27 | 972 | 44 | 0.521 | 23 |
| HUB = DENVER | | | | | | | | | | |
| ALBUQUERQUE | 118 | 27 | 123 | 36 | 0 | 5 | 309 | 15 | 0.562 | 8 |
| DENVER | 603 | 190 | 732 | 437 | 26 | 3 | 1991 | 116 | ----- | -- |
| FT BLISS | 603 | 115 | 539 | 389 | 27 | 3 | 1676 | 97 | 0.726 | 70 |
| HILL AFB | 171 | 72 | 186 | 32 | 20 | 17 | 498 | 19 | 0.606 | 12 |
| WICHITA | 52 | 30 | 46 | 42 | 0 | 1 | 171 | 10 | 0.362 | 4 |
| HUB = BOSTON | | | | | | | | | | |
| ALBANY | 180 | 104 | 181 | 103 | 1 | 1 | 570 | 28 | 0.432 | 12 |
| BOSTON | 3593 | 303 | 2612 | 368 | 97 | 55 | 7028 | 257 | ----- | -- |
| NORTHAMPTON | 233 | 6 | 132 | 66 | 4 | 5 | 446 | 20 | 0.472 | 9 |
| HUB = LOS ANGELES | | | | | | | | | | |
| LOS ANGELES | 4704 | 1343 | 3327 | 1102 | 567 | 473 | 11516 | 468 | ----- | -- |
| LUKE AFB | 371 | 110 | 472 | 47 | 21 | 5 | 1026 | 39 | 0.663 | 26 |
| TUCSON | 169 | 66 | 82 | 35 | 9 | 8 | 369 | 15 | 0.540 | 8 |
| HUB = SAN FRANCISCO | | | | | | | | | | |
| FT LEWIS | 473 | 180 | 450 | 264 | 81 | 77 | 1525 | 78 | 0.624 | 49 |
| PORTLAND | 213 | 64 | 327 | 81 | 15 | 12 | 712 | 35 | 0.540 | 19 |
| SAN FRANCISCO | 897 | 421 | 1481 | 358 | 117 | 56 | 3330 | 157 | ----- | -- |

## Appendix C: Allocation of Patients per Day

TOTAL BEDS

| CATEGORY | MM | MP | SS | SO | SC | SB | TOTAL |
|---|---|---|---|---|---|---|---|
| OVERALL | 40608 | 11058 | 35242 | 11269 | 2401 | 1706 | 102284 |
| PERCENT/CAT. | 0.13 | 0.03 | 0.44 | 0.37 | 0.01 | 0.03 | 1.00 |
| NUM./CAT./DAY | 559 | 142 | 1958 | 1634 | 31 | 115 | 4440 |

TOTAL # OF BEDS PER CATEGORY PER HUB

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CHICAGO | 5811 | 1729 | 6957 | 1946 | 360 | 290 | 17093 |
| ATLANTA | 4048 | 1111 | 3393 | 1228 | 192 | 169 | 10141 |
| HOUSTON | 5903 | 1482 | 4017 | 1277 | 146 | 88 | 12913 |
| PHILADELPHIA | 9412 | 2428 | 7495 | 2281 | 479 | 236 | 22331 |
| CHARLOTTE | 3054 | 1277 | 2690 | 1177 | 239 | 202 | 8639 |
| DENVER | 1547 | 434 | 1626 | 936 | 73 | 29 | 4645 |
| BOSTON | 4006 | 413 | 2925 | 537 | 102 | 61 | 8044 |
| LOS ANGELES | 5244 | 1519 | 3881 | 1184 | 597 | 486 | 12911 |
| SAN FRANCISCO | 1583 | 665 | 2258 | 703 | 213 | 145 | 5567 |

PERCENT OF OVERALL TOTAL # OF BEDS PER CATEGORY PER HUB

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CHICAGO | 0.14 | 0.16 | 0.20 | 0.17 | 0.15 | 0.17 | 0.17 |
| ATLANTA | 0.10 | 0.10 | 0.10 | 0.11 | 0.08 | 0.10 | 0.10 |
| HOUSTON | 0.15 | 0.13 | 0.11 | 0.11 | 0.06 | 0.05 | 0.13 |
| PHILADELPHIA | 0.23 | 0.22 | 0.21 | 0.20 | 0.20 | 0.14 | 0.22 |
| CHARLOTTE | 0.08 | 0.12 | 0.08 | 0.10 | 0.10 | 0.12 | 0.08 |
| DENVER | 0.04 | 0.04 | 0.05 | 0.08 | 0.03 | 0.02 | 0.05 |
| BOSTON | 0.10 | 0.04 | 0.08 | 0.05 | 0.04 | 0.04 | 0.08 |
| LOS ANGELES | 0.13 | 0.14 | 0.11 | 0.11 | 0.25 | 0.28 | 0.13 |
| SAN FRANCISCO | 0.04 | 0.06 | 0.06 | 0.06 | 0.09 | 0.08 | 0.05 |

PATIENTS PER CATEGORY PER HUB PER DAY

| | | | | | | |
|---|---|---|---|---|---|---|
| CHICAGO | 80 | 22 | 387 | 282 | 5 | 20 |
| ATLANTA | 56 | 14 | 189 | 178 | 2 | 11 |
| HOUSTON | 81 | 19 | 223 | 185 | 2 | 6 |
| PHILADELPHIA | 130 | 31 | 416 | 331 | 6 | 16 |
| CHARLOTTE | 42 | 16 | 149 | 171 | 3 | 14 |
| DENVER | 21 | 6 | 90 | 136 | 1 | 2 |
| BOSTON | 55 | 5 | 163 | 78 | 1 | 4 |
| LOS ANGELES | 72 | 20 | 216 | 172 | 8 | 33 |
| SAN FRANCISCO | 22 | 9 | 125 | 102 | 3 | 10 |

PERCENT OF PATIENTS PER CATEGORY PER HOSPITAL WITHIN EACH HUB

| CATEGORY | MM | MP | SS | SO | SC | SB |
|---|---|---|---|---|---|---|
| **HUB= CHICAGO** | | | | | | |
| ALLEN PARK | 0.10 | 0.09 | 0.07 | 0.07 | 0.08 | 0.09 |
| CHICAGO | 0.38 | 0.33 | 0.38 | 0.28 | 0.24 | 0.33 |
| CLEVELAND | 0.06 | 0.11 | 0.04 | 0.05 | 0.11 | 0.11 |
| DES MOINES | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 |
| FT LEAVENWORTH | 0.04 | 0.04 | 0.05 | 0.04 | 0.07 | 0.02 |
| INDIANAPOLIS | 0.04 | 0.04 | 0.01 | 0.02 | 0.02 | 0.01 |
| LEXINGTON | 0.04 | 0.05 | 0.06 | 0.10 | 0.01 | 0.00 |
| MINNEAPOLIS | 0.02 | 0.09 | 0.05 | 0.04 | 0.07 | 0.04 |
| OFFUTT AFB | 0.10 | 0.06 | 0.02 | 0.09 | 0.04 | 0.06 |
| SCOTT AFB | 0.11 | 0.08 | 0.17 | 0.14 | 0.00 | 0.00 |
| WRIGHT-PATT AFB | 0.09 | 0.09 | 0.13 | 0.16 | 0.33 | 0.33 |
| **HUB= ATLANTA** | | | | | | |
| ATLANTA | 0.17 | 0.08 | 0.14 | 0.25 | 0.02 | 0.21 |
| BIRMINGHAM | 0.13 | 0.06 | 0.14 | 0.05 | 0.06 | 0.05 |
| HOMESTEAD AFB | 0.01 | 0.02 | 0.02 | 0.00 | 0.02 | 0.00 |
| JACKSON | 0.08 | 0.15 | 0.09 | 0.02 | 0.08 | 0.05 |
| JACKSONVILLE | 0.11 | 0.17 | 0.12 | 0.29 | 0.28 | 0.34 |
| KNOXVILLE | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.01 |
| MILLINGTON | 0.11 | 0.14 | 0.07 | 0.05 | 0.13 | 0.02 |
| NASHVILLE | 0.12 | 0.18 | 0.14 | 0.13 | 0.07 | 0.03 |
| ORLANDO | 0.22 | 0.14 | 0.21 | 0.16 | 0.30 | 0.30 |
| **HUB= HOUSTON** | | | | | | |
| CARSWELL AFB | 0.12 | 0.10 | 0.12 | 0.14 | 0.36 | 0.00 |
| HOUSTON | 0.21 | 0.17 | 0.30 | 0.31 | 0.03 | 0.30 |
| LITTLE ROCK AFB | 0.01 | 0.01 | 0.02 | 0.07 | 0.00 | 0.00 |
| NEW ORLEANS | 0.39 | 0.43 | 0.32 | 0.25 | 0.54 | 0.26 |
| OKLAHOMA CITY | 0.04 | 0.04 | 0.11 | 0.09 | 0.01 | 0.00 |
| SAN ANTONIO | 0.19 | 0.20 | 0.11 | 0.11 | 0.06 | 0.40 |
| SHREVEPORT | 0.04 | 0.07 | 0.03 | 0.03 | 0.00 | 0.05 |

| CATEGORY | MM | MP | SS | SO | SC | SB |
|---|---|---|---|---|---|---|
| HUB= PHILADELPHIA | | | | | | |
| BUFFALO | 0.09 | 0.05 | 0.09 | 0.09 | 0.05 | 0.07 |
| NORFOLK | 0.13 | 0.21 | 0.14 | 0.19 | 0.05 | 0.19 |
| PHILADELPHIA | 0.45 | 0.53 | 0.45 | 0.34 | 0.48 | 0.43 |
| PITTSBURGH | 0.15 | 0.05 | 0.13 | 0.06 | 0.06 | 0.04 |
| SYRACUSE | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.16 |
| WASHINGTON DC | 0.17 | 0.15 | 0.19 | 0.31 | 0.35 | 0.10 |
| HUB= CHARLOTTE | | | | | | |
| CHARLESTON SC | 0.07 | 0.06 | 0.10 | 0.05 | 0.01 | 0.06 |
| CHARLOTTE | 0.17 | 0.27 | 0.14 | 0.09 | 0.17 | 0.07 |
| FT BRAGG | 0.53 | 0.42 | 0.61 | 0.61 | 0.59 | 0.67 |
| FT GORDON | 0.09 | 0.17 | 0.06 | 0.13 | 0.12 | 0.07 |
| FT JACKSON | 0.14 | 0.09 | 0.09 | 0.13 | 0.10 | 0.13 |
| HUB= DENVER | | | | | | |
| ALBUQUERQUE | 0.08 | 0.06 | 0.08 | 0.04 | 0.00 | 0.17 |
| DENVER | 0.39 | 0.44 | 0.45 | 0.47 | 0.36 | 0.10 |
| FT BLISS | 0.39 | 0.26 | 0.33 | 0.42 | 0.37 | 0.10 |
| HILL AFB | 0.11 | 0.17 | 0.11 | 0.03 | 0.27 | 0.59 |
| WICHITA | 0.03 | 0.07 | 0.03 | 0.04 | 0.00 | 0.03 |
| HUB= BOSTON | | | | | | |
| ALBANY | 0.04 | 0.25 | 0.06 | 0.19 | 0.01 | 0.02 |
| BOSTON | 0.90 | 0.73 | 0.89 | 0.69 | 0.95 | 0.90 |
| NORTHAMPTON | 0.06 | 0.01 | 0.05 | 0.12 | 0.04 | 0.08 |
| HUB= LOS ANGELES | | | | | | |
| LOS ANGELES | 0.90 | 0.88 | 0.86 | 0.93 | 0.95 | 0.97 |
| LUKE AFB | 0.07 | 0.07 | 0.12 | 0.04 | 0.04 | 0.01 |
| TUCSON | 0.03 | 0.04 | 0.02 | 0.03 | 0.02 | 0.02 |
| HUB= SAN FRANCISCO | | | | | | |
| FT LEWIS | 0.30 | 0.27 | 0.20 | 0.38 | 0.38 | 0.53 |
| PORTLAND | 0.13 | 0.10 | 0.14 | 0.12 | 0.07 | 0.08 |
| SAN FRANCISCO | 0.57 | 0.63 | 0.66 | 0.51 | 0.55 | 0.39 |

PATIENTS PER CATEGORY PER HOSPITAL WITHIN EACH HUB

| CATEGORY | MM | MP | SS | SO | SC | SB | TOTAL |
|---|---|---|---|---|---|---|---|
| HUB=CHICAGO | | | | | | | |
| ALLEN PARK | 8 | 2 | 29 | 19 | 1 | 2 | 61 |
| CHICAGO | 30 | 7 | 147 | 79 | 1 | 7 | 271 |
| CLEVELAND | 5 | 3 | 16 | 15 | 1 | 2 | 42 |
| DES MOINES | 1 | 0 | 5 | 2 | 0 | 0 | 8 |
| FT LEAVENWORTH | 3 | 1 | 21 | 12 | 0 | 0 | 37 |
| INDIANAPOLIS | 4 | 1 | 5 | 5 | 1 | 1 | 17 |
| LEXINGTON | 4 | 1 | 22 | 28 | 0 | 0 | 55 |
| MINNEAPOLIS | 1 | 2 | 19 | 11 | 0 | 1 | 34 |
| OFFUTT AFB | 8 | 1 | 7 | 26 | 0 | 1 | 43 |
| SCOTT AFB | 9 | 2 | 68 | 40 | 0 | 0 | 119 |
| WRIGHT-PATT AFB | 7 | 2 | 49 | 46 | 2 | 7 | 113 |
| HUB= ATLANTA | | | | | | | |
| ATLANTA | 10 | 1 | 26 | 45 | 0 | 2 | 84 |
| BIRMINGHAM | 7 | 1 | 27 | 8 | 1 | 1 | 45 |
| HOMESTEAD AFB | 1 | 1 | 5 | 0 | 0 | 0 | 7 |
| JACKSON | 5 | 2 | 18 | 3 | 0 | 1 | 29 |
| JACKSONVILLE | 6 | 2 | 22 | 51 | 1 | 4 | 86 |
| KNOXVILLE | 3 | 1 | 12 | 9 | 0 | 0 | 25 |
| MILLINGTON | 6 | 2 | 14 | 9 | 0 | 0 | 31 |
| NASHVILLE | 6 | 3 | 27 | 23 | 0 | 0 | 59 |
| ORLANDO | 12 | 2 | 39 | 29 | 1 | 3 | 86 |
| HUB= HOUSTON | | | | | | | |
| CARSWELL AFB | 9 | 2 | 28 | 25 | 1 | 0 | 65 |
| HOUSTON | 17 | 3 | 66 | 58 | 0 | 2 | 146 |
| LITTLE ROCK AFB | 1 | 0 | 5 | 12 | 0 | 0 | 18 |
| NEW ORLEANS | 32 | 8 | 71 | 47 | 1 | 2 | 161 |
| OKLAHOMA CITY | 3 | 1 | 23 | 17 | 0 | 0 | 44 |
| SAN ANTONIO | 16 | 4 | 24 | 20 | 0 | 2 | 66 |
| SHREVEPORT | 3 | 1 | 6 | 5 | 0 | 0 | 15 |

| CATEGORY | MM | MP | SS | SO | SC | SB | TOTALS |
|---|---|---|---|---|---|---|---|
| HUB= PHILADELPHIA | | | | | | | |
| BUFFALO | 12 | 2 | 38 | 29 | 1 | 1 | 83 |
| NORFOLK | 17 | 7 | 59 | 63 | 0 | 3 | 149 |
| PHILADELPHIA | 58 | 16 | 187 | 114 | 2 | 7 | 384 |
| PITTSBURGH | 19 | 1 | 53 | 19 | 0 | 1 | 93 |
| SYRACUSE | 4 | 1 | 3 | 2 | 0 | 3 | 13 |
| WASHINGTON DC | 22 | 5 | 78 | 103 | 2 | 2 | 212 |
| HUB= CHARLOTTE | | | | | | | |
| CHARLESTON SC | 3 | 1 | 15 | 9 | 0 | 1 | 29 |
| CHARLOTTE | 7 | 4 | 20 | 15 | 1 | 1 | 48 |
| FT BRAGG | 22 | 7 | 90 | 104 | 2 | 9 | 234 |
| FT GORDON | 4 | 3 | 9 | 22 | 0 | 1 | 39 |
| FT JACKSON | 6 | 1 | 13 | 22 | 0 | 2 | 44 |
| HUB= DENVER | | | | | | | |
| ALBUQUERQUE | 2 | 1 | 7 | 5 | 0 | 0 | 15 |
| DENVER | 8 | 3 | 41 | 64 | 0 | 0 | 116 |
| FT BLISS | 8 | 2 | 30 | 57 | 0 | 0 | 97 |
| HILL AFB | 2 | 1 | 10 | 5 | 0 | 1 | 19 |
| WICHITA | 1 | 0 | 3 | 6 | 0 | 0 | 10 |
| HUB= BOSTON | | | | | | | |
| ALBANY | 2 | 1 | 10 | 15 | 0 | 0 | 28 |
| BOSTON | 49 | 4 | 146 | 53 | 1 | 4 | 257 |
| NORTHAMPTON | 3 | 0 | 7 | 10 | 0 | 0 | 20 |
| HUB= LOS ANGELES | | | | | | | |
| LOS ANGELES | 65 | 18 | 185 | 160 | 8 | 32 | 468 |
| LUKE AFB | 5 | 1 | 26 | 7 | 0 | 0 | 39 |
| TUCSON | 3 | 1 | 5 | 5 | 0 | 1 | 15 |
| HUB= SAN FRANCISCO | | | | | | | |
| FT LEWIS | 7 | 2 | 25 | 38 | 1 | 5 | 78 |
| PORTLAND | 3 | 1 | 18 | 12 | 0 | 1 | 35 |
| SAN FRANCISCO | 12 | 6 | 82 | 52 | 2 | 3 | 157 |

## Appendix D: Distance Matrices per Hub

| HOSPITAL | A.P. | CHIC | CLEV | D.M. | LEAV | IND. | LEX. | MINN | OFF. | SCOT | WPAFB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ALLEN PARK | 0 | 204 | 83 | 462 | 545 | 200 | 257 | 458 | 551 | 366 | 166 |
| CHICAGO | 204 | 0 | 274 | 259 | 350 | 154 | 281 | 290 | 348 | 231 | 231 |
| CLEVELAND | 83 | 274 | 0 | 531 | 601 | 226 | 239 | 539 | 617 | 398 | 152 |
| DES MOINES | 462 | 259 | 531 | 0 | 143 | 353 | 467 | 202 | 90 | 271 | 456 |
| LEAVENWORTH | 545 | 350 | 601 | 143 | 0 | 392 | 480 | 342 | 113 | 251 | 496 |
| INDIANAPOLIS | 200 | 154 | 226 | 353 | 392 | 0 | 128 | 436 | 431 | 172 | 105 |
| LEXINGTON | 257 | 281 | 239 | 467 | 480 | 128 | 0 | 564 | 537 | 232 | 92 |
| MINNEAPOLIS | 458 | 290 | 539 | 202 | 342 | 436 | 564 | 0 | 251 | 427 | 520 |
| OFFUTT | 551 | 348 | 617 | 90 | 113 | 431 | 537 | 251 | 0 | 324 | 535 |
| SCOTT | 366 | 231 | 398 | 271 | 251 | 172 | 232 | 427 | 324 | 0 | 266 |
| WRIGHT-PATT AF | 166 | 231 | 152 | 456 | 496 | 105 | 92 | 520 | 535 | 266 | 0 |

HUB = ATLANTA

| HOSPITAL | ATLA | BIRM | HOME | JACK | JVIL | KNOX | MILL | NASH | ORLA |
|---|---|---|---|---|---|---|---|---|---|
| ATLANTA | 0 | 117 | 546 | 295 | 235 | 132 | 288 | 186 | 351 |
| BIRMINGHAM | 117 | 0 | 601 | 183 | 317 | 192 | 188 | 154 | 416 |
| HOMESTEAD AFB | 546 | 601 | 0 | 666 | 322 | 660 | 781 | 729 | 197 |
| JACKSON | 295 | 183 | 666 | 0 | 443 | 368 | 183 | 284 | 510 |
| JACKSONVILLE | 235 | 317 | 322 | 443 | 0 | 340 | 504 | 421 | 126 |
| KNOXVILLE | 132 | 192 | 660 | 368 | 340 | 0 | 288 | 132 | 463 |
| MILLINGTON | 288 | 188 | 781 | 183 | 504 | 288 | 0 | 162 | 601 |
| NASHVILLE | 186 | 154 | 729 | 284 | 421 | 132 | 162 | 0 | 536 |
| ORLANDO | 351 | 416 | 197 | 510 | 126 | 463 | 601 | 536 | 0 |

HUB = HOUSTON

| HOSPITAL | CARS | HOUS | LITT | N.O. | OKLA | S.A. | SHRE |
|---|---|---|---|---|---|---|---|
| CARSWELL AFB | 0 | 217 | 288 | 389 | 168 | 202 | 196 |
| HOUSTON | 217 | 0 | 347 | 255 | 370 | 171 | 197 |
| LITTLE ROCK | 288 | 347 | 0 | 289 | 257 | 451 | 150 |
| NEW ORLEANS | 389 | 255 | 289 | 0 | 473 | 425 | 213 |
| OKLAHOMA CITY | 168 | 370 | 257 | 473 | 0 | 366 | 261 |
| SAN ANTONIO | 202 | 171 | 451 | 425 | 366 | 0 | 315 |
| SHREVEPORT | 196 | 197 | 150 | 213 | 261 | 315 | 0 |

HUB = PHILADELPHIA

| HOSPITAL | BUFFALO | NORFOLK | PHILADELPHIA | PITTSBURGH | SYRACUSE | WASHINGTON DC |
|---|---|---|---|---|---|---|
| BUFFALO | 0 | 381 | 242 | 162 | 116 | 286 |
| NORFOLK | 381 | 0 | 184 | 287 | 373 | 97 |
| PHILADELPHIA | 242 | 184 | 0 | 232 | 198 | 102 |
| PITTSBURGH | 162 | 287 | 232 | 0 | 243 | 210 |
| SYRACUSE | 116 | 373 | 198 | 243 | 0 | 278 |
| WASHINGTON DC | 286 | 97 | 102 | 210 | 278 | 0 |

HUB = CHARLOTTE

| HOSPITAL | CHARLESTON SC | CHARLOTTE | FT BRAGG | FT GORDON | FT JACKSON |
|---|---|---|---|---|---|
| CHARLESTON SC | 0 | 146 | 146 | 101 | 83 |
| CHARLOTTE | 146 | 0 | 95 | 122 | 77 |
| FT BRAGG | 146 | 95 | 0 | 182 | 128 |
| FT GORDON | 101 | 122 | 182 | 0 | 54 |
| FT JACKSON | 83 | 77 | 128 | 54 | 0 |

HUB = DENVER

| HOSPITAL | ALBUQUERQUE | DENVER | FT BLISS | HILL AFB | WICHITA |
|---|---|---|---|---|---|
| ALBUQUERQUE | 0 | 280 | 191 | 439 | 467 |
| DENVER | 280 | 0 | 464 | 341 | 364 |
| FT BLISS | 191 | 464 | 0 | 607 | 563 |
| HILL AFB | 439 | 341 | 607 | 0 | 705 |
| WICHITA | 467 | 364 | 563 | 705 | 0 |

HUB = BOSTON

| HOSPITAL | ALBANY | BOSTON | NORTHAMPTON |
|---|---|---|---|
| ALBANY | 0 | 123 | 71 |
| BOSTON | 123 | 0 | 60 |
| NORTHAMPTON | 71 | 60 | 0 |

HUB = LOS ANGELES

| HOSPITAL | LOS ANGELES | LUKE AFB | TUCSON |
|---|---|---|---|
| LOS ANGELES | 0 | 311 | 411 |
| LUKE AFB | 311 | 0 | 113 |
| TUCSON | 411 | 113 | 0 |

HUB = SAN FRANCISCO

| HOSPITAL | FT LEWIS | PORTLAND | SAN FRANCISCO |
|---|---|---|---|
| FT LEWIS | 0 | 90 | 568 |
| PORTLAND | 90 | 0 | 478 |
| SAN FRANCISCO | 568 | 478 | 0 |

## Appendix E: Time to Fly Matrices per Hub (in Block Hours)

| HOSPITAL | A.P. | CHIC | CLEV | D.M. | LEAV | IND. | LEX. | MINN | OFF. | SCOT | WPAFB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ALLEN PARK | 0.00 | 0.68 | 0.28 | 1.54 | 1.82 | 0.67 | 0.86 | 1.53 | 1.84 | 1.22 | 0.55 |
| CHICAGO | 0.68 | 0.00 | 0.91 | 0.86 | 1.17 | 0.51 | 0.94 | 0.97 | 1.16 | 0.77 | 0.77 |
| CLEVELAND | 0.28 | 0.91 | 0.00 | 1.77 | 2.00 | 0.75 | 0.80 | 1.80 | 2.06 | 1.33 | 0.51 |
| DES MOINES | 1.54 | 0.86 | 1.77 | 0.00 | 0.48 | 1.18 | 1.56 | 0.67 | 0.30 | 0.90 | 1.52 |
| FT LEAVENWORTH | 1.82 | 1.17 | 2.00 | 0.48 | 0.00 | 1.31 | 1.60 | 1.14 | 0.38 | 0.84 | 1.65 |
| INDIANAPOLIS | 0.67 | 0.51 | 0.75 | 1.18 | 1.31 | 0.00 | 0.43 | 1.45 | 1.44 | 0.57 | 0.35 |
| LEXINGTON | 0.86 | 0.94 | 0.80 | 1.56 | 1.60 | 0.43 | 0.00 | 1.88 | 1.79 | 0.77 | 0.31 |
| MINNEAPOLIS | 1.53 | 0.97 | 1.80 | 0.67 | 1.14 | 1.45 | 1.88 | 0.00 | 0.84 | 1.42 | 1.73 |
| OFFUTT AFB | 1.84 | 1.16 | 2.06 | 0.30 | 0.38 | 1.44 | 1.79 | 0.84 | 0.00 | 1.08 | 1.78 |
| SCOTT AFB | 1.22 | 0.77 | 1.33 | 0.90 | 0.84 | 0.57 | 0.77 | 1.42 | 1.08 | 0.00 | 0.89 |
| WRIGHT-PATT | 0.55 | 0.77 | 0.51 | 1.52 | 1.65 | 0.35 | 0.31 | 1.73 | 1.78 | 0.89 | 0.00 |

HUB = ATLANTA

| HOSPITAL | ATLA | BIRM | HOME | JACK | J.V. | KNOX | MILL | NASH | ORLA |
|---|---|---|---|---|---|---|---|---|---|
| ATLANTA | 0.00 | 0.39 | 1.82 | 0.98 | 0.78 | 0.44 | 0.96 | 0.62 | 1.17 |
| BIRMINGHAM | 0.39 | 0.00 | 2.00 | 0.61 | 1.06 | 0.64 | 0.63 | 0.51 | 1.39 |
| HOMESTEAD | 1.82 | 2.00 | 0.00 | 2.22 | 1.07 | 2.20 | 2.60 | 2.43 | 0.66 |
| JACKSON | 0.98 | 0.61 | 2.22 | 0.00 | 1.48 | 1.23 | 0.61 | 0.95 | 1.70 |
| JACKSONVILLE | 0.78 | 1.06 | 1.07 | 1.48 | 0.00 | 1.13 | 1.68 | 1.40 | 0.42 |
| KNOXVILLE | 0.44 | 0.64 | 2.20 | 1.23 | 1.13 | 0.00 | 0.96 | 0.44 | 1.54 |
| MILLINGTON | 0.96 | 0.63 | 2.60 | 0.61 | 1.68 | 0.96 | 0.00 | 0.54 | 2.00 |
| NASHVILLE | 0.62 | 0.51 | 2.43 | 0.95 | 1.40 | 0.44 | 0.54 | 0.00 | 1.79 |
| ORLANDO | 1.17 | 1.39 | 0.66 | 1.70 | 0.42 | 1.54 | 2.00 | 1.79 | 0.00 |

HUB = HOUSTON

| HOSPITAL | CARS | HOUS | LITT | N.O. | OKLA | S.A. | SHRE |
|---|---|---|---|---|---|---|---|
| CARSWELL AFB | 0.00 | 0.72 | 0.96 | 1.30 | 0.56 | 0.67 | 0.65 |
| HOUSTON | 0.72 | 0.00 | 1.16 | 0.85 | 1.23 | 0.57 | 0.66 |
| LITTLE ROCK | 0.96 | 1.16 | 0.00 | 0.96 | 0.86 | 1.50 | 0.50 |
| NEW ORLEANS | 1.30 | 0.85 | 0.96 | 0.00 | 1.58 | 1.42 | 0.71 |
| OKLAHOMA CITY | 0.56 | 1.23 | 0.86 | 1.58 | 0.00 | 1.22 | 0.87 |
| SAN ANTONIO | 0.67 | 0.57 | 1.50 | 1.42 | 1.22 | 0.00 | 1.05 |
| SHREVEPORT | 0.65 | 0.66 | 0.50 | 0.71 | 0.87 | 1.05 | 0.00 |

HUB = PHILADELPHIA

| HOSPITAL | BUFFALO | NORFOLK | PHILADELPHIA | PITTSBURGH | SYRACUSE | WASHINGTON DC |
|---|---|---|---|---|---|---|
| BUFFALO | 0.00 | 1.27 | 0.81 | 0.54 | 0.39 | 0.95 |
| NORFOLK | 1.27 | 0.00 | 0.61 | 0.96 | 1.24 | 0.32 |
| PHILADELPHIA | 0.81 | 0.61 | 0.00 | 0.77 | 0.66 | 0.34 |
| PITTSBURGH | 0.54 | 0.96 | 0.77 | 0.00 | 0.81 | 0.70 |
| SYRACUSE | 0.39 | 1.24 | 0.66 | 0.81 | 0.00 | 0.93 |
| WASHINGTON DC | 0.95 | 0.32 | 0.34 | 0.70 | 0.93 | 0.00 |

HUB = CHARLOTTE

| HOSPITAL | CHARLESTON SC | CHARLOTTE | FT BRAGG | FT GORDON | FT JACKSON |
|---|---|---|---|---|---|
| CHARLESTON SC | 0.00 | 0.49 | 0.49 | 0.34 | 0.28 |
| CHARLOTTE | 0.49 | 0.00 | 0.32 | 0.41 | 0.26 |
| FT BRAGG | 0.49 | 0.32 | 0.00 | 0.61 | 0.43 |
| FT GORDON | 0.34 | 0.41 | 0.61 | 0.00 | 0.18 |
| FT JACKSON | 0.28 | 0.26 | 0.43 | 0.18 | 0.00 |

HUB = DENVER

| HOSPITAL | ALBUQUERQUE | DENVER | FT BLISS | HILL AFB | WICHITA |
|---|---|---|---|---|---|
| ALBUQUERQUE | 0.00 | 0.93 | 0.64 | 1.46 | 1.56 |
| DENVER | 0.93 | 0.00 | 1.55 | 1.14 | 1.21 |
| FT BLISS | 0.64 | 1.55 | 0.00 | 2.02 | 1.88 |
| HILL AFB | 1.46 | 1.14 | 2.02 | 0.00 | 2.35 |
| WICHITA | 1.56 | 1.21 | 1.88 | 2.35 | 0.00 |

HUB = BOSTON

| HOSPITAL | ALBANY | BOSTON | NORTHAMPTON |
|---|---|---|---|
| ALBANY | 0.00 | 0.41 | 0.24 |
| BOSTON | 0.41 | 0.00 | 0.20 |
| NORTHAMPTON | 0.24 | 0.20 | 0.00 |

HUB = LOS ANGELES

| HOSPITAL | LOS ANGELES | LUKE AFB | TUCSON |
|---|---|---|---|
| LOS ANGELES | 0.00 | 1.04 | 1.37 |
| LUKE AFB | 1.04 | 0.00 | 0.38 |
| TUCSON | 1.37 | 0.38 | 0.00 |

HUB = SAN FRANCISCO

| HOSPITAL | FT LEWIS | PORTLAND | SAN FRANCISCO |
|---|---|---|---|
| FT LEWIS | 0.00 | 0.30 | 1.89 |
| PORTLAND | 0.30 | 0.00 | 1.59 |
| SAN FRANCISCO | 1.89 | 1.59 | 0.00 |

## Appendix F: Example SLAM Input

```
GEN,BRAND CARTER,CHARLESTON,1/1/90,,,,//,72;
LIMITS,6,1,600;
NETWORK;
        CREATE,1,1;
MM      ASSIGN,ATRIB(1)=3;
        UNBATCH,1;
        QUEUE(1),,0,BALK(NA);
          ACT(212)/1,RNORM(16,1.6),,TM;
        CREATE,1,1;
MP      ASSIGN,ATRIB(1)=1;
        UNBATCH,1;
        QUEUE(2),,0,BALK(NB);
          ACT(78)/2,RNORM(29,2.9),,TM;
        CREATE,1,1;
SS      ASSIGN,ATRIB(1)=15;
        UNBATCH,1;
        QUEUE(3),,0,BALK(NC);
          ACT(277)/3,RNORM(24,2.4),,TM;
        CREATE,1,1;
SO      ASSIGN,ATRIB(1)=9;
        UNBATCH,1;
        QUEUE(4),,0,BALK(ND);
          ACT(62)/4,RNORM(50,5.0),,TM;
;        CREATE,1,1;
;SC      ASSIGN,ATRIB(1)=1;
;        UNBATCH,1;
;        QUEUE(5),,0,BALK(NE);
;          ACT(25)/5,RNORM(38,3.8),,TM;
        CREATE,1,1;
SB      ASSIGN,ATRIB(1)=1;
        UNBATCH,1;
        QUEUE(6),,0,BALK(NF);
          ACT(12)/6,RNORM(33,3.3),,TM;
NA      GOON;
          ACT/9,,,NR;     TOTAL # MM TURNED AWAY
NB      GOON;
          ACT/10,,,NR;    TOTAL # MP TURNED AWAY
NC      GOON;
          ACT/11,,,NR;    TOTAL # SS TURNED AWAY
ND      GOON;
          ACT/12,,,NR;    TOTAL # SO TURNED AWAY
NE      GOON;
          ACT/13,,,NR;    TOTAL # SC TURNED AWAY
NF      GOON;
          ACT/14,,,NR;    TOTAL # SB TURNED AWAY
NR      GOON;
          ACT/7,,,TT;     TOTAL # NOT SERVED
TM      GOON;
          ACT/8;          TOTAL # SERVED
TT      GOON;
          ACT/15;         TOTAL # ENTITIES
        TERM;
        END;
INIT,0,365,NO;
FIN;
```

# Appendix G: Example SLAM Output

S L A M   I I   S U M M A R Y   R E P O R T

SIMULATION PROJECT CHARLESTON                BY BRAND CARTER

DATE  1/ 1/1990                              RUN NUMBER    1 OF    1

CURRENT TIME   0.3650E+03
STATISTICAL ARRAYS CLEARED AT TIME  0.0000E+00

**FILE STATISTICS**

| FILE NUMBER | LABEL/TYPE | AVERAGE LENGTH | STANDARD DEVIATION | MAXIMUM LENGTH | CURRENT LENGTH | AVERAGE WAIT TIME |
|---|---|---|---|---|---|---|
| 1 | QUEUE | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 2 | QUEUE | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 3 | QUEUE | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 4 | QUEUE | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 5 | | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 6 | QUEUE | 0.000 | 0.000 | 0 | 0 | 0.000 |
| 7 | CALENDAR | 415.254 | 51.760 | 450 | 436 | 3.180 |

**REGULAR ACTIVITY STATISTICS**

| ACTIVITY INDEX/LABEL | AVERAGE UTILIZATION | STANDARD DEVIATION | MAXIMUM UTIL | CURRENT UTIL | ENTITY COUNT |
|---|---|---|---|---|---|
| 7 TOTAL # NOT | 0.0000 | 0.0000 | 1 | 0 | 4354 |
| 8 TOTAL # SERV | 0.0000 | 0.0000 | 1 | 0 | 5800 |
| 9 TOTAL # MM T | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 10 TOTAL # MP T | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 11 TOTAL # SS T | 0.0000 | 0.0000 | 1 | 0 | 1314 |
| 12 TOTAL # SO T | 0.0000 | 0.0000 | 1 | 0 | 2812 |
| 13 TOTAL # SC T | 0.0000 | 0.0000 | 0 | 0 | 0 |
| 14 TOTAL # SB T | 0.0000 | 0.0000 | 1 | 0 | 228 |
| 15 TOTAL # ENTI | 0.0000 | 0.0000 | 1 | 0 | 10154 |

**SERVICE ACTIVITY STATISTICS**

| ACT NUM | ACT LABEL OR START NODE | SER CAP | AVERAGE UTIL | STD DEV | CUR UTIL | AVERAGE BLOCK | MAX IDL TME/SER | MAX BSY TME/SER | ENT CNT |
|---|---|---|---|---|---|---|---|---|---|
| 1 | QUEUE | 212 | 46.565 | 6.17 | 50 | 0.00 | 212.00 | 55.00 | 1045 |
| 2 | QUEUE | 78 | 27.715 | 4.84 | 30 | 0.00 | 78.00 | 34.00 | 335 |
| 3 | QUEUE | 277 | 263.721 | 35.79 | 277 | 0.00 | 277.00 | 277.00 | 3884 |
| 4 | QUEUE | 62 | 60.760 | 5.43 | 62 | 0.00 | 62.00 | 62.00 | 411 |
| 6 | QUEUE | 12 | 11.494 | 1.42 | 12 | 0.00 | 12.00 | 12.00 | 125 |

## Appendix H: Example Vehicle Routing Problem Input

```
MODEL:
  1) MIN= .32 * X121 + .32 * X122 + .41 * X131 + .41 * X132 + .49 * X141 +
     .49 * X142 + .32 * X211 + .32 * X212 + .61 * X231 + .61 * X232 + .49
     * X241 + .49 * X242 + .41 * X311 + .41 * X312 + .61 * X321 + .61 *
     X322 + .34 * X341 + .34 * X342 + .49 * X411 + .49 * X412 + .49 * X421
     + .49 * X422 + .34 * X431 + .34 * X432 ;
  2) X121 + X131 + X141 = 1 ;
  3) X122 + X132 + X142 = 1 ;
  4) X211 + X311 + X411 = 1 ;
  5) X212 + X312 + X412 = 1 ;
  6) X121 + X122 + X321 + X322 + X421 + X422 = 1 ;
  7) X211 + X212 + X231 + X232 + X241 + X242 = 1 ;
  8) X131 + X132 + X231 + X232 + X431 + X432 = 1 ;
  9) X311 + X312 + X321 + X322 + X341 + X342 = 1 ;
 10) X141 + X142 + X241 + X242 + X341 + X342 = 1 ;
 11) X411 + X412 + X421 + X422 + X431 + X432 = 1 ;
 12) X121 + X211 < 2 ;
 13) X122 + X212 < 2 ;
 14) X131 + X311 < 2 ;
 15) X132 + X312 < 2 ;
 16) X141 + X411 < 2 ;
 17) X142 + X412 < 2 ;
 18) X231 + X232 + X321 + X322 < 1 ;
 19) X241 + X242 + X421 + X422 < 1 ;
 20) X341 + X342 + X431 + X432 < 1 ;
 21) 29 * X121 + 19 * X131 + 19 * X141 + 19 * X231 + 19 * X241 + 29 * X321
     + 19 * X341 + 29 * X421 + 19 * X431 < 48 ;
 22) 29 * X122 + 19 * X132 + 19 * X142 + 19 * X232 + 19 * X242 + 29 * X322
     + 19 * X342 + 29 * X422 + 19 * X432 < 48 ;
END

LEAVE
```

## Appendix I: Example Vehicle Routing Problem Output

SOLUTION STATUS: OPTIMAL TO TOLERANCES. DUAL CONDITIONS: SATISFIED.

OBJECTIVE FUNCTION VALUE

1) 1.880000

| VARIABLE | VALUE | REDUCED COST |
|---|---|---|
| X121 | 1.000000 | .000000 |
| X122 | .000000 | .000000 |
| X131 | .000000 | .000000 |
| X132 | .000000 | .000000 |
| X141 | .000000 | .000000 |
| X142 | 1.000000 | .000000 |
| X211 | 1.000000 | .000000 |
| X212 | .000000 | .000000 |
| X231 | .000000 | .000000 |
| X232 | .000000 | .000000 |
| X241 | .000000 | .000000 |
| X242 | .000000 | .000000 |
| X311 | .000000 | .000000 |
| X312 | 1.000000 | .000000 |
| X321 | .000000 | .000000 |
| X322 | .000000 | .000000 |
| X341 | .000000 | .000000 |
| X342 | .000000 | .000000 |
| X411 | .000000 | .000000 |
| X412 | .000000 | .000000 |
| X421 | .000000 | .000000 |
| X422 | .000000 | .000000 |
| X431 | .000000 | .000000 |
| X432 | 1.000000 | .000000 |

## Appendix J: Spacefilling Curve Calculating Basic Program

```
10 DIM A$(100),X(100),Y(100),XX(100),YY(100),NR(100)
20 DIM TH(100),IQ(100),Z(100),ZZ(100),GX(100),GY(100)
30 INPUT "HOW MANY BINARY DIGITS (10 DEFAULT)?";K
40 PRINT:IF K=0 THEN K=10
50 KP=2^(K-1)
60 INPUT "HOW MANY DIMENSIONS (2 OR 3)?";DM:PRINT
70 INPUT "INPUT FILE NAME";FILE$:PRINT
80 INPUT "OUTPUT TEXT FILE NAME";FOUT$:PRINT
90 INPUT "OUTPUT DELIMITED FILE NAME";DOUT$:PRINT
100 OPEN FILE$ FOR INPUT AS #1
110 PRINT FILE$ " OPENED":PRINT
120 REM COUNT NUMBER OF LOCATIONS
130 FOR I = 1 TO 100
140 IF EOF(1) THEN 170
150 INPUT #1,A$(I),GX(I),GY(I),X(I),Y(I)
160 NEXT I
170 N=I-1
180 CLOSE #1:PRINT FILE$ " CLOSED, "  N " POINTS":PRINT
190 IF DM=3 THEN GOTO 780
200 HIX=0: HIY=0: LOX=400: LOY=400
210 FOR I = 1 TO N
220 PRINT X(I),Y(I)
230 IF HIX<X(I) THEN HIX=X(I)
240 IF HIY<Y(I) THEN HIY=Y(I)
250 PRINT HIX,HIY
260 NEXT I
270 FOR I = 1 TO N
280 PRINT X(I),Y(I)
290 IF LOX>X(I) THEN LOX=X(I)
300 IF LOY>Y(I) THEN LOY=Y(I)
310 PRINT LOX,LOY
320 NEXT I
330 SPDX=HIX - LOX: SPDY=HIY - LOY
340 PRINT SPDX,SPDY
350 IF SPDX >=SPDY THEN S = SPDX ELSE S=SPDY
360 PRINT "SIDE OF SQUARE = " S:PRINT: LOZ=0
370 FOR I = 1 TO N
380 XX(I)=X(I)-LOX: YY(I)= Y(I)-LOY: ZZ(I)= Z(I)-LOZ
390 NEXT I
400 U=S*.501/KP
410 FOR I=1 TO N: GOSUB 560 :NEXT I
420 FOR I=1 TO N: NR(I)=I:NEXT I: GOSUB 650
430 OPEN FOUT$ FOR OUTPUT AS #2
440 IF DM=3 THEN GOTO 1000
450 PRINT#2,:PRINT#2, TAB(1)"RANK"TAB(7)"NAME"TAB(27)"LATITUDE"TAB(41)"LONGITUDE" TAB(55)"THETA"
460 PRINT:PRINT TAB(1)"RANK"TAB(7)"NAME"TAB(27)"LATITUDE"TAB(41)"LONGITUDE"TAB(55)"THETA":PRINT
470 FOR I=1 TO N:J=NR(I)
480 PRINT#2, TAB(1) I TAB(7) A$(J) TAB(27) GX(J) TAB(41) GY(J) TAB(55) TH(J)
```

```
490 PRINT TAB(1) I TAB(7) A$(J) TAB(27) GX(J) TAB(41) GY(J) TAB(55) TH(J):NEXT I
500 CLOSE #2
510 OPEN DOUT$ FOR OUTPUT AS #3
520 IF DM=3 THEN GOTO 1080
530 FOR I = 1 TO N:J=NR(I)
540 WRITE#3,A$(J),TH(J):NEXT I
550 CLOSE #3:STOP
560 REM theta calculating subroutine
570 KX=INT(XX(I)/U): KY=INT(YY(I)/U): KZ=INT(ZZ(I)/U)
580 FOR J=1 TO K: JX=INT(KX/KP): JY=INT(KY/KP): JZ=INT(KZ/KP)
590 KX=2*(KX-KP*JX): KY=2*(KY-KP*JY): KZ=2*(KZ-KP*JZ)
600 IQ(J)=JY+3*JX+7*JZ-2*JX*JY-2*JY*JZ-6*JX*JZ-6*JX*JY*JZ: NEXT J
610 IF DM=3 THEN T=IQ(K)/8 ELSE T=IQ(K)/4
620 FOR J=K-1 TO 1 STEP -1: IF DM=3 THEN T=T+(14-IQ(J))/8 ELSE T=T+(6-IQ(J))/4
630 T=T-INT(T): IF DM=3 THEN T=(7.5+T+IQ(J))/8 ELSE T=(3.5+T+IQ(J))/4:NEXT J
640 TH(I)=T-INT(T): RETURN
650 REM subroutine for sorting thetas
660 IL=INT(N/2)+1:IR=N
670 IF IL>1 THEN IL=IL-1: NA=NR(IL): GOTO 700
680 NA=NR(IR): NR(IR)=NR(1): IR=IR-1
690 IF IR=1 THEN NR(1)=NA:RETURN
700 TA=TH(NA):J=IL
710 I=J: J=2*J:IF J=IR THEN GOTO 740
720 IF J>IR THEN GOTO 760
730 IF TH(NR(J))<TH(NR(J+1)) THEN J=J+1
740 IF TA>=TH(NR(J)) THEN GOTO 760
750 NR(I)=NR(J):GOTO 710
760 NR(I)=NA: GOTO 670
770 REM 3 DIMENSIONAL SIZING ROUTINE
780 HIX=0: HIY=0: LOX=400: LOY=400: HIZ=0: LOZ=100
790 FOR I = 1 TO N
800 PRINT "# OF PATIENTS FOR AIRLIFT TO " A$(I) "?":INPUT;Z(I):PRINT:NEXT I
810 FOR I = 1 TO N
820 PRINT X(I),Y(I),Z(I)
830 IF HIX<X(I) THEN HIX=X(I)
840 IF HIY<Y(I) THEN HIY=Y(I)
850 IF HIZ<Z(I) THEN HIZ=Z(I)
860 PRINT HIX,HIY,HIZ
870 NEXT I
880 FOR I = 1 TO N
890 PRINT X(I),Y(I),Z(I)
900 IF LOX>X(I) THEN LOX=X(I)
910 IF LOY>Y(I) THEN LOY=Y(I)
920 IF LOZ>Z(I) THEN LOZ=Z(I)
930 PRINT LOX,LOY,LOZ
940 NEXT I
950 SPDX=HIX - LOX: SPDY=HIY - LOY: SPDZ=HIZ - LOZ
960 PRINT SPDX,SPDY,SPDZ
970 IF SPDX >=SPDY THEN S = SPDX ELSE S=SPDY
980 IF SPDZ>S THEN S = SPDZ
990 PRINT "SIDE OF SQUARE = " S:PRINT: GOTO 370
```

```
1000
PRINT#2,TAB(1)"RANK"TAB(7)"NAME"TAB(26)"LATITUDE"TAB(37)"LONGITUDE"TAB(48)"PATIENTS"TAB(59)"THETA"
1010 PRINT TAB(1)"RANK"TAB(7)"NAME"TAB(26)"LATITUDE"TAB(37)"LONGITUDE"TAB(48)"PATIENTS"TAB(59)"THETA"
1020 PRINT#2,
1030 PRINT
1040 FOR I=1 TO N: J=NR(I)
1050 PRINT#2,TAB(1) I TAB(7) A$(J) TAB(26) GX(J) TAB(37) GY(J) TAB(48) Z(J) TAB(59) TH(J)
1060 PRINT TAB(1) I TAB(7) A$(J) TAB(26) GX(J) TAB(37) GY(J) TAB(48) Z(J) TAB(59) TH(J)
1070 NEXT I: GOTO 500
1080 FOR I = 1 TO N:J=NR(I)
1090 WRITE#3,A$(J),TH(J),Z(J):NEXT I:GOTO 550
1100 END
```

The following text is found in the READ.ME file on the floppy disk provided to Dr. Chan:

```
Welcome to the Spacefilling Curve Heuristic Program!

This disk holds the capability to accomplish 2 and 3 dimensional
spacefilling curves.

The contents of this disk are as follows:
1)GWBASIC executable file
2)SFC.BAS a basic program with the spacefilling curve calculations
3)Several sample text files (delimited)

HOW TO USE THIS DISK!

I. Put disk in drive A: and change to drive A: (unless you
   copy the contents of the disk to a hard drive directory)

II. At the A:\ prompt, type GWBASIC (this enters you into the
    BASIC program)

III. Once the Basic program is ready, press F3 and type SFC
     or type LOAD"SFC

IV. Next, press F2 or type RUN

V. Now just answer the questions!

VI. Each time you want to run the SFC program you must press
    F2 or type RUN.

VII.When you are done using the program, type SYSTEM
    this will return you to the A:\ prompt.
```

The *.TXT files are good examples of how input data files must be set up.

EXAMPLE: (BOST.TXT)

"ALBANY",42.650,73.750,314,37
"BOSTON",42.363,71.007,331,34
"NORTHAMPTON",42.118,72.318,325,37

This program was originally designed for use with global positions converted to grid positions. The first value must be a name for its associated point and must be enclosed in "". The next two values are latitude and longitude in this example but have no significance to the program except for the final printout. As with any delimited file, though, you must include the commas even if you do not put any thing in these positions. The last two values are grid conversions of the latitude and longitude which were calculated outside the program. They are the values the space filling curve heuristic actually uses to transform a two or three dimensional space into the unit interval (for 3 dimensional problems the program will prompt for the third dimension for each point while it is executing).

If you are using a Euclidean space other than the global space mentioned here, input is still quite easy. For example, say you have points 1,2,and 3. Their x-y coordinates are (1,1), (2,2) and (3,3) respectively. The input file should read:

"1",,,1,1
"2",,,2,2
"3",,,3,3

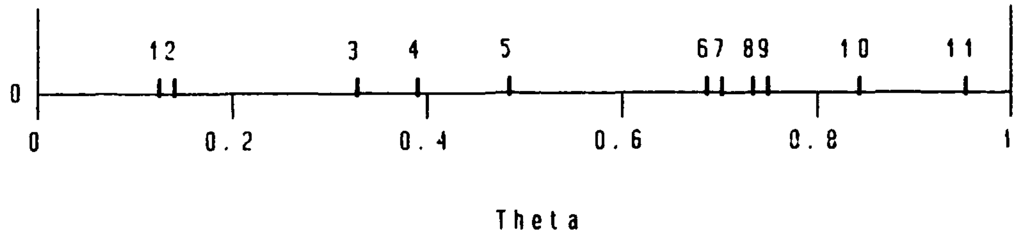
In a 2 dimensional calculation the theta values (the unit interval values) will be produced normally. For a 3 dimensional problem the program will ask for the z coordinate for each point. The question will refer to the # of patients, take this to mean the z value.

GOOD LUCK and have fun.

The Spacefilling curve is an amazingly versatile tool.
Any questions call MAC XPY, Major Brand Carter, AV576-5560

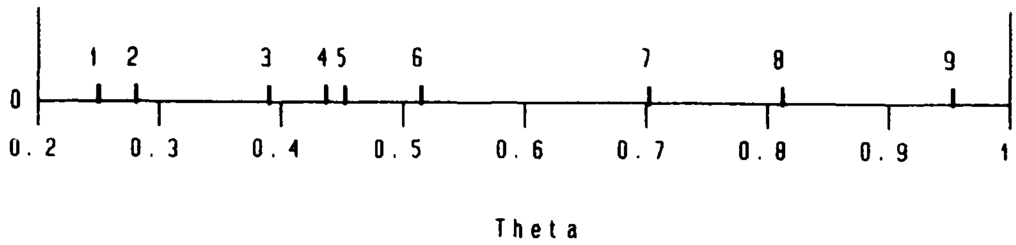
Appendix K: 3-Dimensional Spacefilling Curve Results For Unrestricted Hospitals / All Expected Patients

CHICAGO HUB



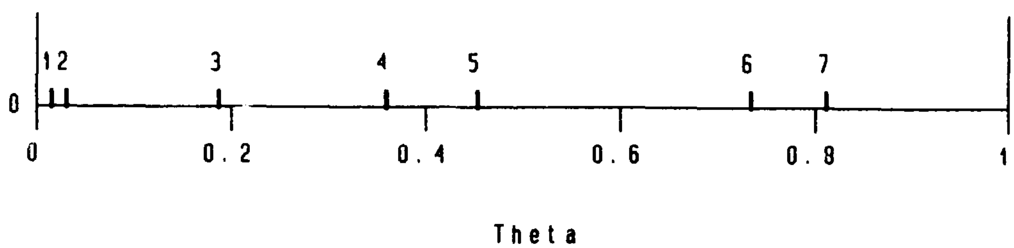

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | INDIANAPOLIS | 39.725 | 86.283 | 17 | .125 |
| 2 | DES MOINES | 41.535 | 93.66001 | 8 | .140625 |
| 3 | SCOTT AFB | 38.326 | 89.511 | 119 | .328125 |
| 4 | CHICAGO | 41.98 | 87.905 | 0 | .390625 |
| 5 | CLEVELAND | 41.412 | 81.85 | 42 | .484375 |
| 6 | OFFUTT AFB | 41.071 | 95.547 | 43 | .6875 |
| 7 | FT LEAVENWORTH | 39.298 | 94.725 | 37 | .703125 |
| 8 | LEXINGTON | 38.037 | 84.60501 | 55 | .734375 |
| 9 | WRIGHT-PATT AFB | 39.496 | 84.029 | 113 | .75 |
| 10 | MINNEAPOLIS | 44.885 | 93.21499 | 34 | .84375 |
| 11 | ALLEN PARK | 42.215 | 83.348 | 61 | .953125 |

## ATLANTA HUB



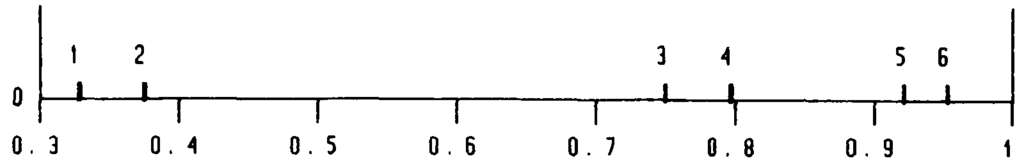

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | BIRMINGHAM | 33.563 | 86.755 | 45 | .25 |
| 2 | HOMESTEAD AFB | 25.293 | 80.23001 | 7 | .28125 |
| 3 | ATLANTA | 33.64 | 84.427 | 0 | .390625 |
| 4 | ORLANDO | 28.428 | 81.317 | 86 | .4375 |
| 5 | JACKSONVILLE | 30.493 | 81.69 | 86 | .453125 |
| 6 | KNOXVILLE | 35.812 | 83.99299 | 25 | .515625 |
| 7 | JACKSON | 32.312 | 90.07701 | 29 | .703125 |
| 8 | MILLINGTON | 35.355 | 89.87 | 31 | .8125 |
| 9 | NASHVILLE | 36.127 | 86.682 | 49 | .953125 |

## HOUSTON HUB



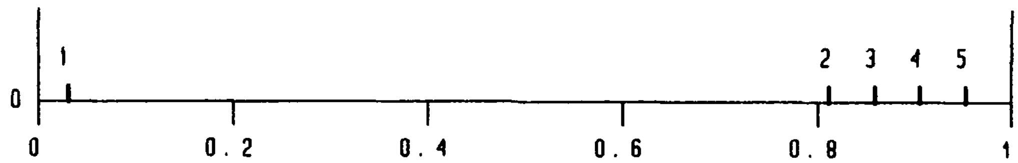

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | LITTLE ROCK AFB | 34.55 | 92.088 | 18 | .015625 |
| 2 | OKLAHOMA CITY | 35.251 | 97.233 | 44 | .03125 |
| 3 | SHREVEPORT | 32.301 | 93.398 | 15 | .1875 |
| 4 | HOUSTON | 29.364 | 95.095 | 0 | .359375 |
| 5 | NEW ORLEANS | 29.992 | 90.252 | 161 | .453125 |
| 6 | CARSWELL AFB | 32.461 | 97.265 | 65 | .734375 |
| 7 | SAN ANTONIO | 29.228 | 98.35 | 66 | .8125 |

## PHILADELPHIA HUB



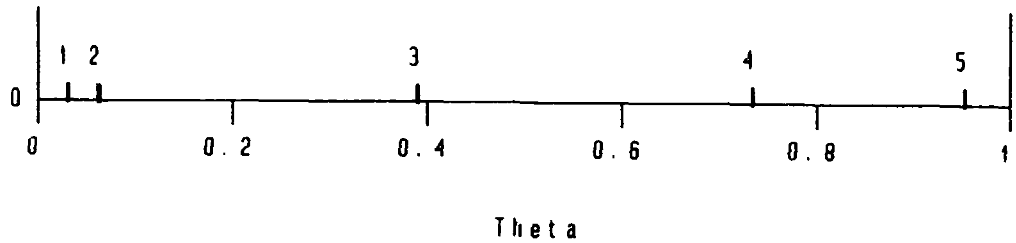

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | NORFOLK | 36.895 | 76.2 | 149 | .328125 |
| 2 | PHILADELPHIA | 39.87 | 75.245 | 0 | .375 |
| 3 | WASHINGTON DC | 38.487 | 76.52 | 212 | .75 |
| 4 | PITTSBURGH | 40.492 | 80.232 | 93 | .796875 |
| 5 | BUFFALO | 42.94 | 78.733 | 83 | .921875 |
| 6 | SYRACUSE | 43.11 | 76.103 | 13 | .953125 |

## CHARLOTTE HUB




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | CHARLOTTE | 35.213 | 80.943 | 0 | .03125 |
| 2 | FT GORDON | 33.37 | 81.965 | 39 | .8125 |
| 3 | FT BRAGG | 35.17 | 79.015 | 234 | .859375 |
| 4 | FT JACKSON | 33.94 | 81.12 | 44 | .90625 |
| 5 | CHARLESTON SC | 32.898 | 80.04 | 29 | .953125 |

DENVER HUB




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | HILL AFB | 41.076 | 111.583 | 19 | .03125 |
| 2 | ALBUQUERQUE | 35.025 | 106.364 | 15 | .0625 |
| 3 | WICHITA | 37.374 | 97.16001 | 10 | .390625 |
| 4 | FT BLISS | 31.85 | 106.38 | 97 | .734375 |
| 5 | DENVER | 39.426 | 104.455 | 0 | .953125 |

BOSTON HUB

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | BOSTON | 42.363 | 71.00701 | 0 | .359375 |
| 2 | NORTHAMPTON | 42.118 | 72.318 | 20 | .84375 |
| 3 | ALBANY | 42.65 | 73.75 | 28 | .90625 |

LOS ANGELES HUB

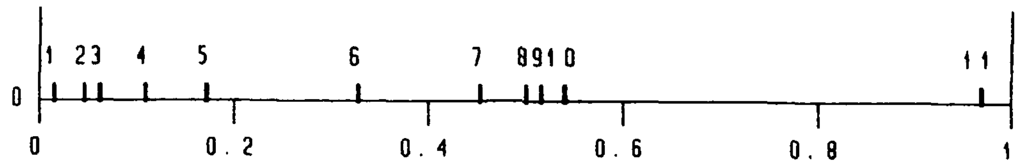
| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | LOS ANGELES | 33.942 | 118.407 | 0 | .03125 |
| 2 | LUKE AFB | 33.321 | 112.229 | 39 | .421875 |
| 3 | TUCSON | 32.099 | 110.529 | 15 | .9375 |

SAN FRANCISCO HUB

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | SAN FRANCISCO | 37.618 | 122.373 | 0 | .046875 |
| 2 | PORTLAND | 45.588 | 122.597 | 35 | .34375 |
| 3 | FT LEWIS | 47.083 | 122.578 | 78 | .84375 |

## Appendix L: 3-Dimensional Spacefilling Curve Results For Restricted Hospitals / Probabilistic Patients

CHICAGO HUB

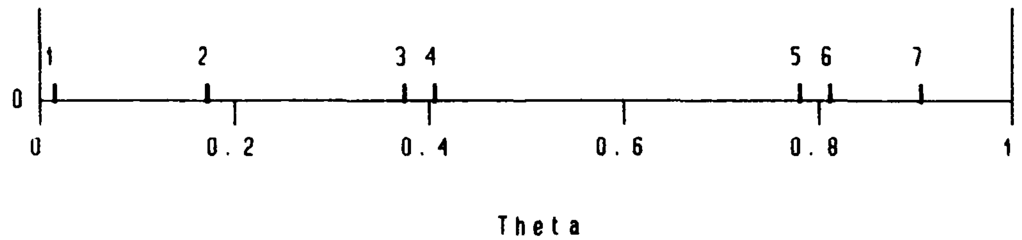



| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | FT LEAVENWORTH | 39.298 | 94.725 | 21 | .015625 |
| 2 | CHICAGO | 41.98 | 87.905 | 0 | .046875 |
| 3 | DES MOINES | 41.535 | 93.66001 | 5 | .0625 |
| 4 | OFFUTT AFB | 41.071 | 95.547 | 18 | .109375 |
| 5 | INDIANAPOLIS | 39.725 | 86.283 | 9 | .171875 |
| 6 | WRIGHT-PATT AFB | 39.496 | 84.029 | 83 | .328125 |
| 7 | LEXINGTON | 38.037 | 84.60501 | 35 | .453125 |
| 8 | CLEVELAND | 41.412 | 81.85 | 29 | .5 |
| 9 | ALLEN PARK | 42.215 | 83.348 | 43 | .515625 |
| 10 | SCOTT AFB | 38.326 | 89.511 | 82 | .53125 |
| 11 | MINNEAPOLIS | 44.885 | 93.21499 | 18 | .96875 |

ATLANTA HUB


| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | MILLINGTON | 35.355 | 89.87 | 19 | 0 |
| 2 | JACKSON | 32.312 | 90.07701 | 20 | .109375 |
| 3 | HOMESTEAD AFB | 25.293 | 80.23001 | 5 | .28125 |
| 4 | BIRMINGHAM | 33.563 | 86.755 | 29 | .359375 |
| 5 | ATLANTA | 33.64 | 84.427 | 0 | .390625 |
| 6 | KNOXVILLE | 35.812 | 83.99299 | 14 | .421875 |
| 7 | JACKSONVILLE | 30.493 | 81.69 | 64 | .46875 |
| 8 | ORLANDO | 28.428 | 81.317 | 66 | .484375 |
| 9 | NASHVILLE | 36.127 | 86.682 | 36 | .859375 |

HOUSTON HUB

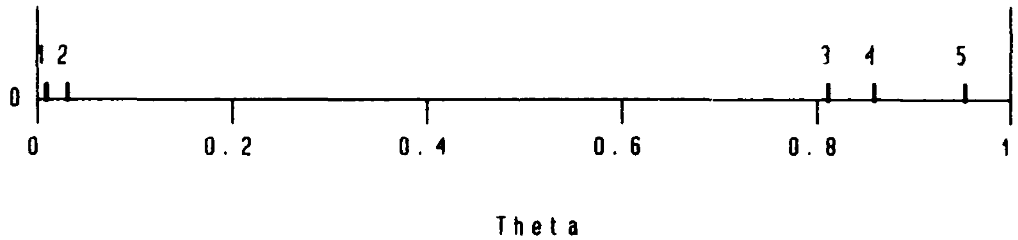



| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | OKLAHOMA CITY | 35.251 | 97.233 | 23 | .015625 |
| 2 | HOUSTON | 29.364 | 95.095 | 0 | .171875 |
| 3 | SHREVEPORT | 32.301 | 93.398 | 9 | .375 |
| 4 | LITTLE ROCK AFB | 34.55 | 92.088 | 6 | .40625 |
| 5 | NEW ORLEANS | 29.992 | 90.252 | 105 | .78125 |
| 6 | CARSWELL AFB | 32.461 | 97.265 | 32 | .8125 |
| 7 | SAN ANTONIO | 29.228 | 98.35 | 48 | .90625 |

PHILADELPHIA HUB

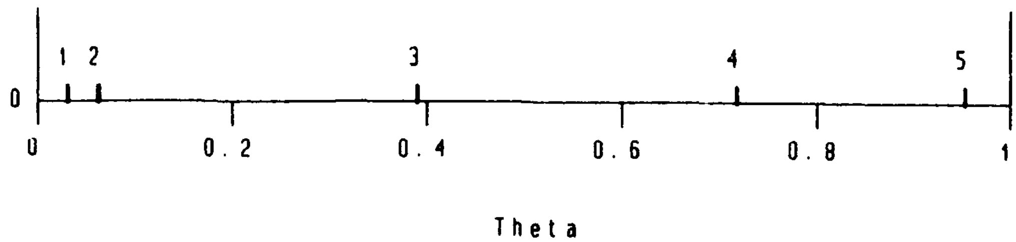

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | SYRACUSE | 43.11 | 76.103 | 8 | .03125 |
| 2 | NORFOLK | 36.895 | 76.2 | 108 | .078125 |
| 3 | WASHINGTON DC | 38.487 | 76.52 | 151 | .84375 |
| 4 | PITTSBURGH | 40.492 | 80.232 | 63 | .890625 |
| 5 | BUFFALO | 42.94 | 78.733 | 51 | .921875 |
| 6 | PHILADELPHIA | 39.87 | 75.245 | 0 | .9375 |

CHARLOTTE HUB




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | FT GORDON | 33.37 | 81.965 | 17 | 0 |
| 2 | CHARLOTTE | 35.213 | 80.943 | 0 | .03125 |
| 3 | FT JACKSON | 33.94 | 81.12 | 23 | .8125 |
| 4 | FT BRAGG | 35.17 | 79.015 | 162 | .859375 |
| 5 | CHARLESTON SC | 32.898 | 80.04 | 17 | .953125 |

## DENVER HUB




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | HILL AFB | 41.076 | 111.583 | 12 | .03125 |
| 2 | ALBUQUERQUE | 35.025 | 106.364 | 8 | .0625 |
| 3 | WICHITA | 37.374 | 97.16001 | 4 | .390625 |
| 4 | FT BLISS | 31.85 | 106.38 | 70 | .71875 |
| 5 | DENVER | 39.426 | 104.455 | 0 | .953125 |

## BOSTON HUB

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | NORTHAMPTON | 42.118 | 72.318 | 9 | .0625 |
| 2 | ALBANY | 42.65 | 73.75 | 12 | .109375 |
| 3 | BOSTON | 42.363 | 71.00701 | 0 | .40625 |

## LOS ANGELES HUB

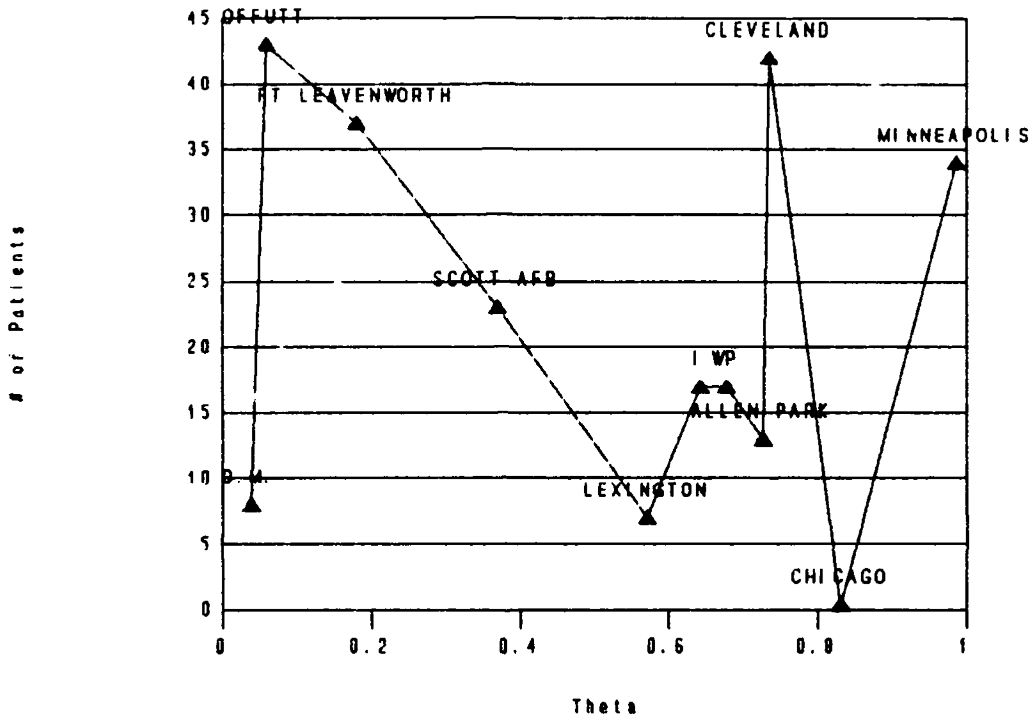
| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | LOS ANGELES | 33.942 | 118.407 | 0 | 0 |
| 2 | TUCSON | 32.099 | 110.529 | 8 | .375 |
| 3 | LUKE AFB | 33.321 | 112.229 | 26 | .5 |

## SAN FRANCISCO HUB

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | SAN FRANCISCO | 37.618 | 122.373 | 0 | .15625 |
| 2 | FT LEWIS | 47.083 | 122.578 | 49 | .359375 |
| 3 | PORTLAND | 45.588 | 122.597 | 19 | .9375 |

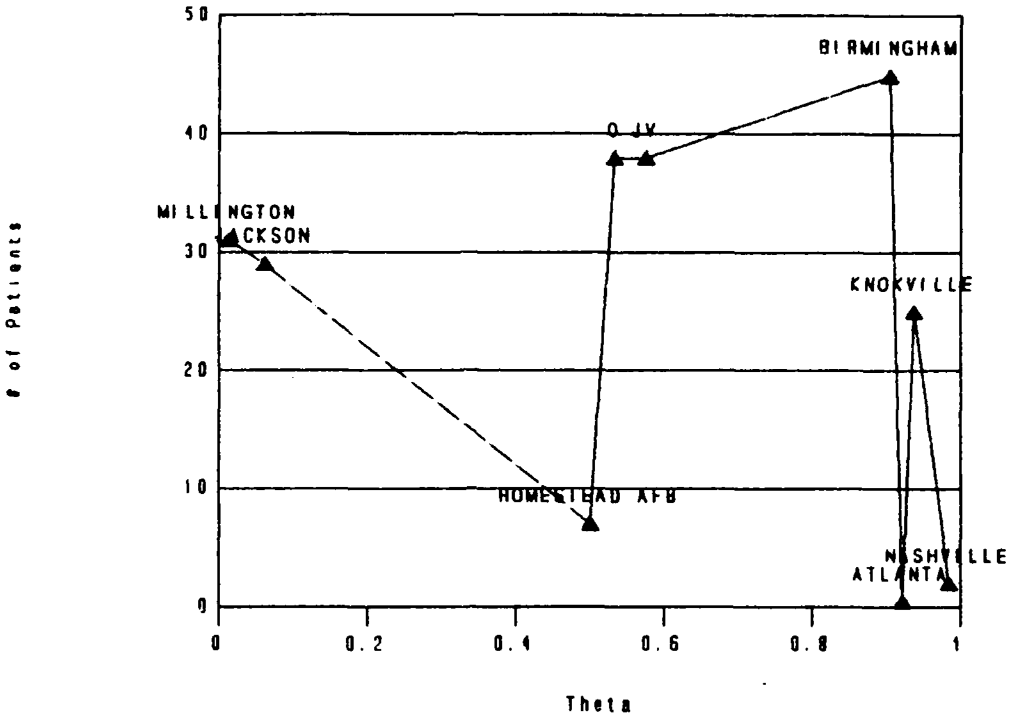
Appendix M: <u>2-Dimensional Spacefilling Curve Results For Unrestricted Hospitals After All Out-and-Backs Have Been Completed</u> (Y-axis added for purposes of utilizing Bartholdi and Platzman suggested VRP solution method)

1. Chicago Hub



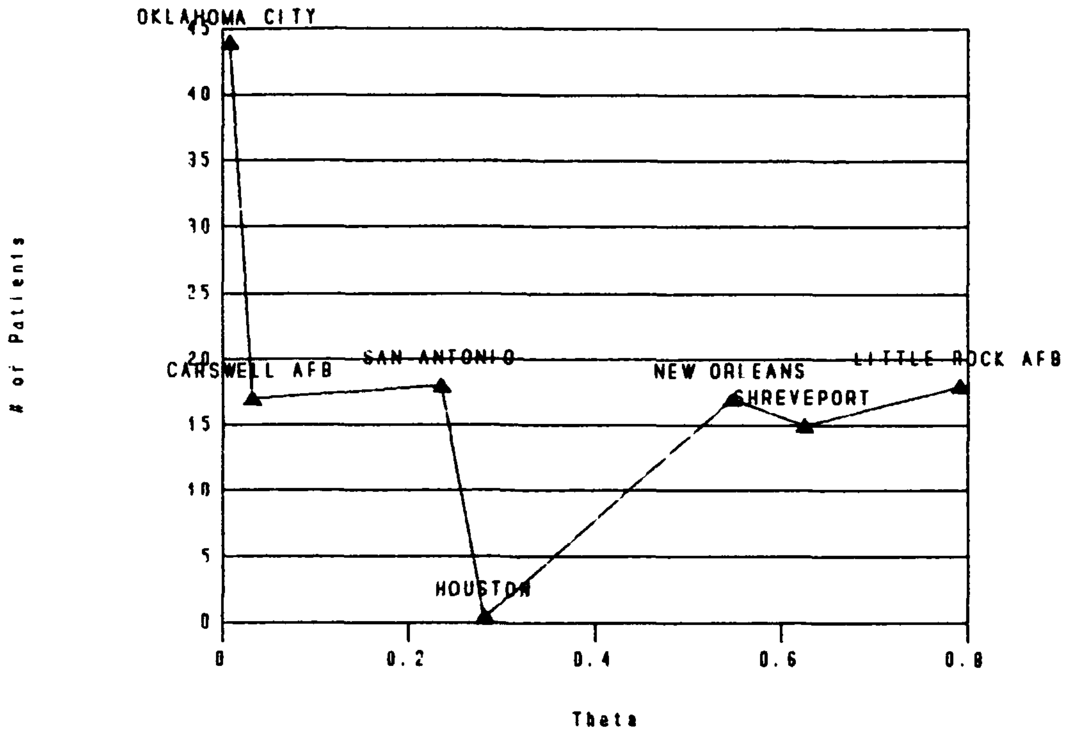

| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | DES MOINES | 41.535 | 93.66001 | 0.038086 |
| 2 | OFFUTT AFB | 41.071 | 95.547 | 0.058594 |
| 3 | FT LEAVENWORTH | 39.298 | 94.725 | .1806641 |
| 4 | SCOTT AFB | 38.326 | 89.511 | .3691406 |
| 5 | LEXINGTON | 38.037 | 84.60501 | .5712891 |
| 6 | INDIANAPOLIS | 39.725 | 86.283 | .6425781 |
| 7 | WRIGHT-PATT AFB | 39.496 | 84.029 | .6777344 |
| 8 | ALLEN PARK | 42.215 | 83.348 | .7265625 |
| 9 | CLEVELAND | 41.412 | 81.85 | .7353516 |
| 10 | CHICAGO | 41.98 | 87.905 | .8310547 |
| 11 | MINNEAPOLIS | 44.885 | 93.21499 | .9873047 |

## 2. Atlanta Hub



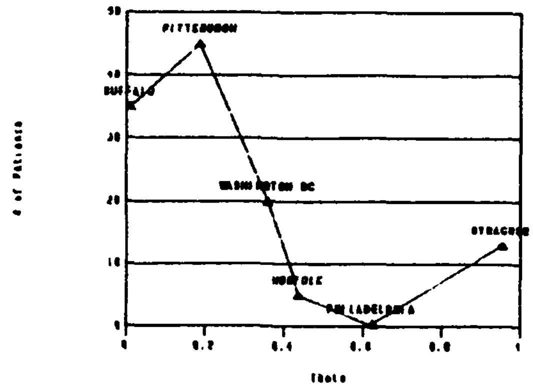

| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | MILLINGTON | 35.355 | 89.87 | 0.012695 |
| 2 | JACKSON | 32.312 | 90.07701 | 0.061523 |
| 3 | HOMESTEAD AFB | 25.293 | 80.23001 | .5 |
| 4 | ORLANDO | 28 428 | 81.317 | .5332031 |
| 5 | JACKSONVILLE | 30.493 | 81.69 | .5761719 |
| 6 | BIRMINGHAM | 33.563 | 86.755 | .9042969 |
| 7 | ATLANTA | 33.64 | 84.427 | .921875 |
| 8 | KNOXVILLE | 35.812 | 83.99299 | .9375 |
| 9 | NASHVILLE | 36.127 | 86.682 | .984375 |

3. Houston Hub



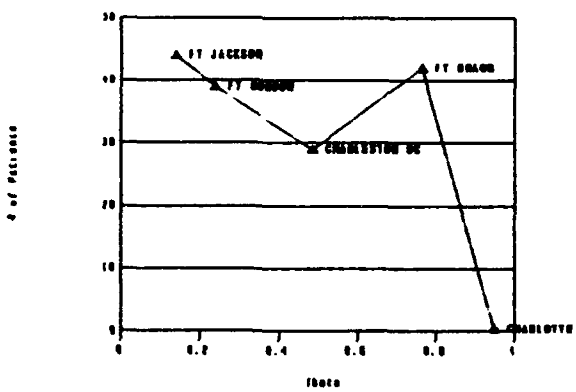

| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | OKLAHOMA CITY | 35.251 | 97.233 | 0 |
| 2 | CARSWELL AFB | 32.461 | 97.265 | .03125 |
| 3 | SAN ANTONIO | 29.228 | 98.35 | .234375 |
| 4 | HOUSTON | 29.364 | 95.095 | .28125 |
| 5 | NEW ORLEANS | 29.992 | 90.252 | .546875 |
| 6 | SHREVEPORT | 32.301 | 93.398 | .625 |
| 7 | LITTLE ROCK AFB | 34.55 | 92.088 | .796875 |

## 4. Philadelphia Hub



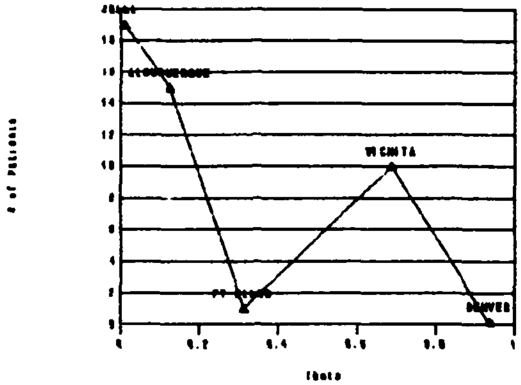
| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | BUFFALO | 42.94 | 78.733 | 0 |
| 2 | PITTSBURGH | 40.492 | 80.232 | .1875 |
| 3 | WASHINGTON DC | 38.487 | 76.52 | .359375 |
| 4 | NORFOLK | 36.895 | 76.2 | .4375 |
| 5 | PHILADELPHIA | 39.87 | 75.245 | .625 |
| 6 | SYRACUSE | 43.11 | 76.103 | .953125 |

## 5. Charlotte Hub



| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | FT JACKSON | 33.94 | 81.12 | .1386719 |
| 2 | Fi GORDON | 33.37 | 81.965 | .2382813 |
| 3 | CHARLESTON SC | 32.898 | 80.04 | .4853516 |
| 4 | FT BRAGG | 35.17 | 79.015 | .7646485 |
| 5 | CHARLOTTE | 35.213 | 80.943 | .9482422 |

## 6. Denver Hub



| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | HILL AFB | 41.076 | 111.583 | 0 |
| 2 | ALBUQUERQUE | 35.025 | 106.364 | .125 |
| 3 | FT BLISS | 31.85 | 106.38 | .3125 |
| 4 | WICHITA | 37.374 | 97.16001 | .6875 |
| 5 | DENVER | 39.426 | 104.455 | .9375 |

## 7. Boston Hub

| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | ALBANY | 42.65 | 73.75 | 0 |
| 2 | BOSTON | 42.363 | 71.00701 | .75 |
| 3 | NORTHAMPTON | 42.118 | 72.318 | .8125 |

## 8. Los Angeles Hub

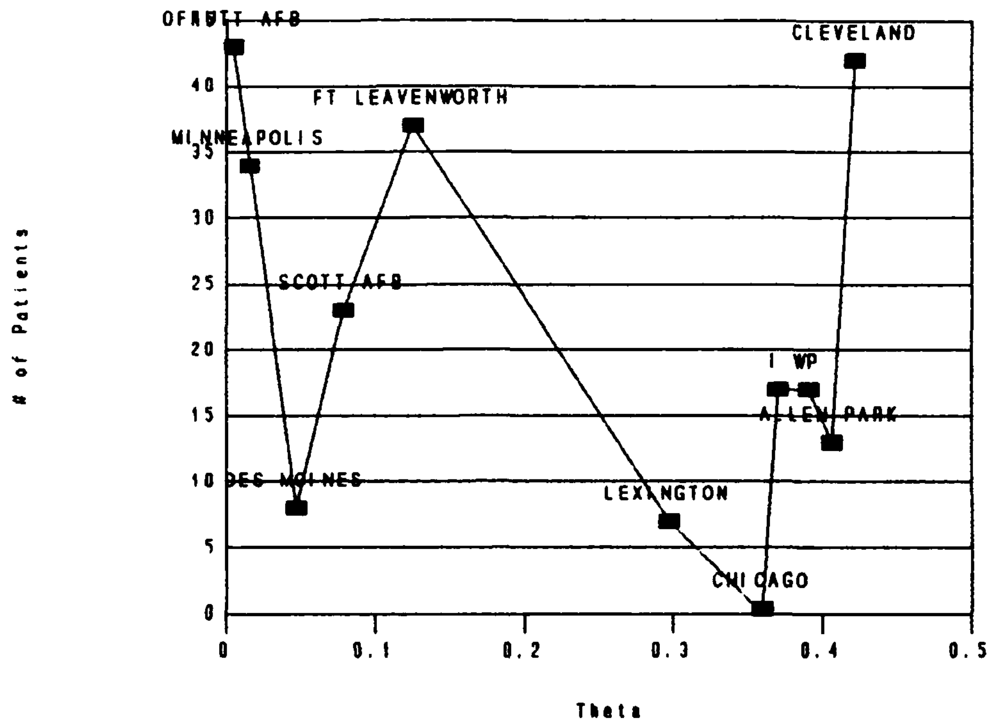
| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | LOS ANGELES | 33.942 | 118.407 | 0 |
| 2 | TUCSON | 32.099 | 110.529 | .6875 |
| 3 | LUKE AFB | 33.321 | 112.229 | .75 |

## 9. San Francisco Hub

| RANK | NAME | LATITUDE | LONGITUDE | THETA |
|---|---|---|---|---|
| 1 | SAN FRANCISCO | 37.618 | 122.373 | .25 |
| 2 | PORTLAND | 45.588 | 122.597 | .96875 |
| 3 | FT LEWIS | 47.083 | 122.578 | .984375 |

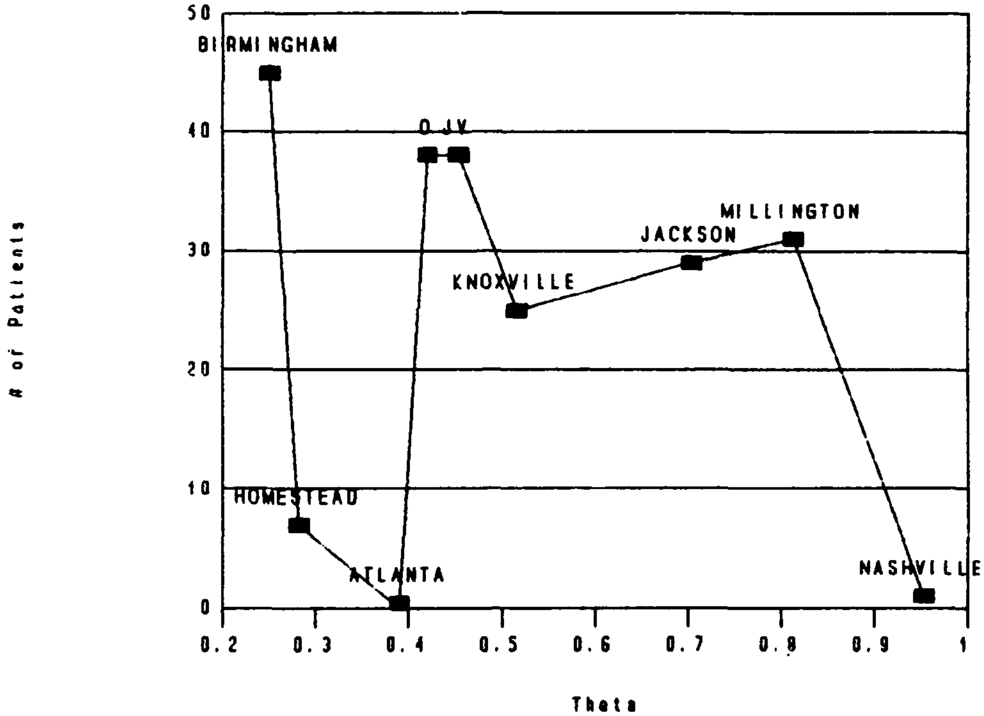
Appendix N: 3-dimensional Spacefilling Curve Results For Unrestricted Hospitals After All Out-and-Backs Have Been Completed

1. Chicago Hub



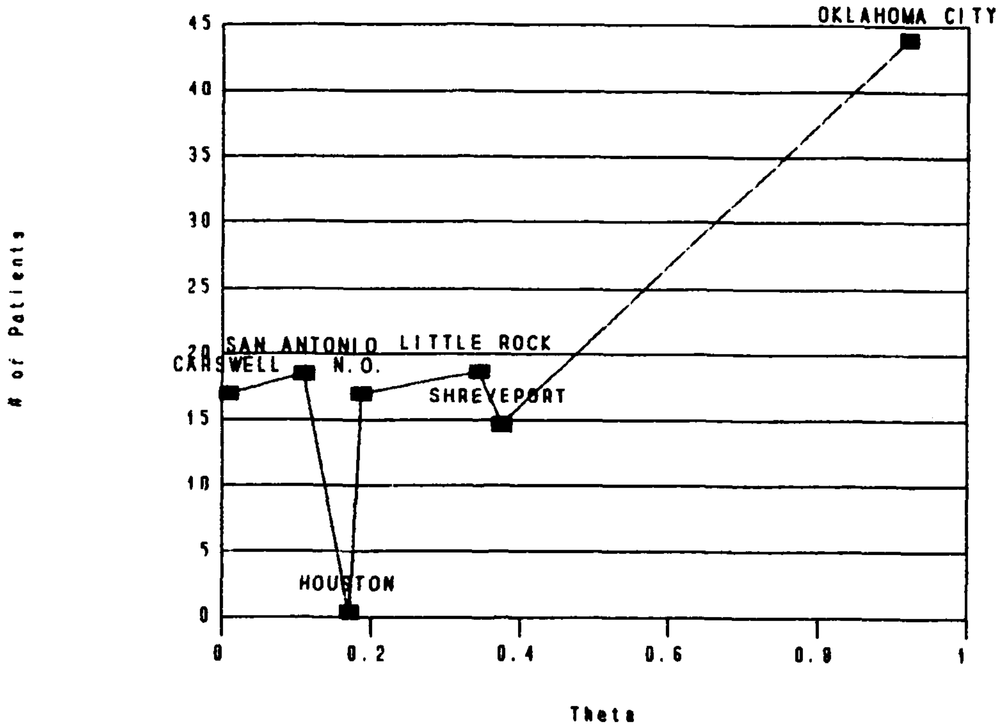

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | OFFUTT AFB | 41.071 | 95.547 | 43 | 0 |
| 2 | MINNEAPOLIS | 44.885 | 93.21499 | 34 | .015625 |
| 3 | DES MOINES | 41.535 | 93.66001 | 8 | .046875 |
| 4 | SCOTT AFB | 38.326 | 89.511 | 23 | .078125 |
| 5 | FT LEAVENWORTH | 39.298 | 94.725 | 37 | .125 |
| 6 | LEXINGTON | 38.037 | 84.60501 | 7 | .296875 |
| 7 | CHICAGO | 41.98 | 87.905 | 0 | .359375 |
| 8 | INDIANAPOLIS | 39.725 | 86.283 | 17 | .375 |
| 9 | WRIGHT-PATT AFB | 39.496 | 84.029 | 17 | .390625 |
| 10 | ALLEN PARK | 42.215 | 83.348 | 13 | .40625 |
| 11 | CLEVELAND | 41.412 | 81.85 | 42 | .421875 |

## 2. Atlanta Hub



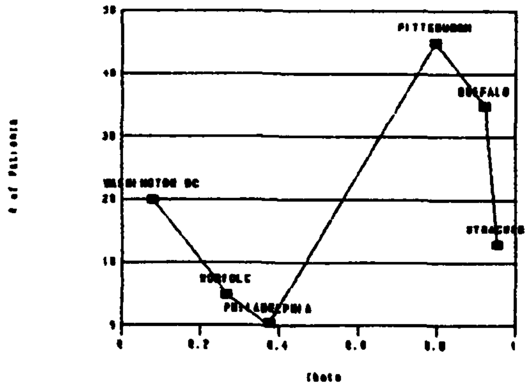

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | BIRMINGHAM | 33.563 | 86.755 | 45 | .25 |
| 2 | HOMESTEAD AFB | 25.293 | 80.23001 | 7 | .28125 |
| 3 | ATLANTA | 33.64 | 84.427 | 0 | .390625 |
| 4 | ORLANDO | 28.428 | 81.317 | 38 | .4375 |
| 5 | JACKSONVILLE | 30.493 | 81.69 | 38 | .453125 |
| 6 | KNOXVILLE | 35.812 | 83.99299 | 25 | .515625 |
| 7 | JACKSON | 32.312 | 90.07701 | 29 | .703125 |
| 8 | MILLINGTON | 35.355 | 89.87 | 31 | .8125 |
| 9 | NASHVILLE | 36.127 | 86.682 | 1 | .953125 |

## 3. Houston Hub



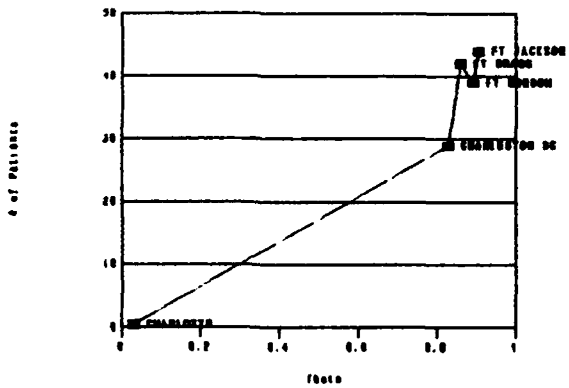

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | CARSWELL AFB | 32.461 | 97.265 | 17 | 0 |
| 2 | SAN ANTONIO | 29.228 | 98.35 | 18 | .109375 |
| 3 | HOUSTON | 29.364 | 95.095 | 0 | .171875 |
| 4 | NEW ORLEANS | 29.992 | 90.252 | 17 | .1875 |
| 5 | LITTLE ROCK AFB | 34.55 | 92.088 | 18 | .34375 |
| 6 | SHREVEPORT | 32.301 | 93.398 | 15 | .375 |
| 7 | OKLAHOMA CITY | 35.251 | 97.233 | 44 | .921875 |

## 4. Philadelphia Hub



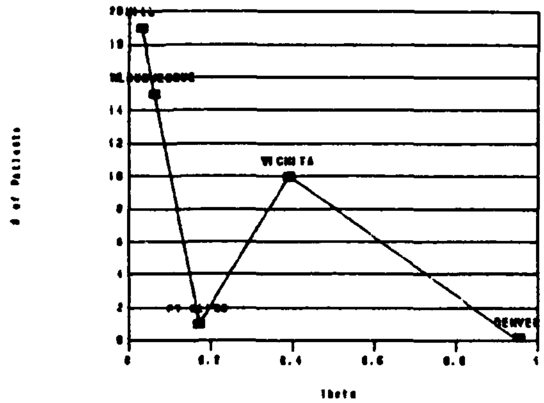

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | WASHINGTON DC | 38.487 | 76.52 | 20 | .078125 |
| 2 | NORFOLK | 36.895 | 76.2 | 5 | .265625 |
| 3 | PHILADELPHIA | 39.87 | 75.245 | 0 | .375 |
| 4 | PITTSBURGH | 40.492 | 80.232 | 45 | .796875 |
| 5 | BUFFALO | 42.94 | 78.733 | 35 | .921875 |
| 6 | SYRACUSE | 43.11 | 76.103 | 13 | .953125 |

## 5. Charlotte Hub




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | CHARLOTTE | 35.213 | 80.943 | 0 | .03125 |
| 2 | CHARLESTON SC | 32.898 | 80.04 | 29 | .828125 |
| 3 | FT BRAGG | 35.17 | 79.015 | 42 | .859375 |
| 4 | FT GORDON | 33.37 | 81.965 | 39 | .890625 |
| 5 | FT JACKSON | 33.94 | 81.12 | 44 | .90625 |

## 6. Denver Hub



| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | HILL AFB | 41.076 | 111.583 | 19 | .03125 |
| 2 | ALBUQUERQUE | 35.025 | 106.364 | 15 | .0625 |
| 3 | FT BLISS | 31.85 | 106.38 | 1 | .171875 |
| 4 | WICHITA | 37.374 | 97.16001 | 10 | .390625 |
| 5 | DENVER | 39.426 | 104.455 | 0 | .953125 |

## 7. Boston Hub

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | BOSTON | 42.363 | 71.00701 | 0 | .359375 |
| 2 | NORTHAMPTON | 42.118 | 72.318 | 20 | .84375 |
| 3 | ALBANY | 42.65 | 73.75 | 28 | .90625 |

## 8. Los Angeles Hub

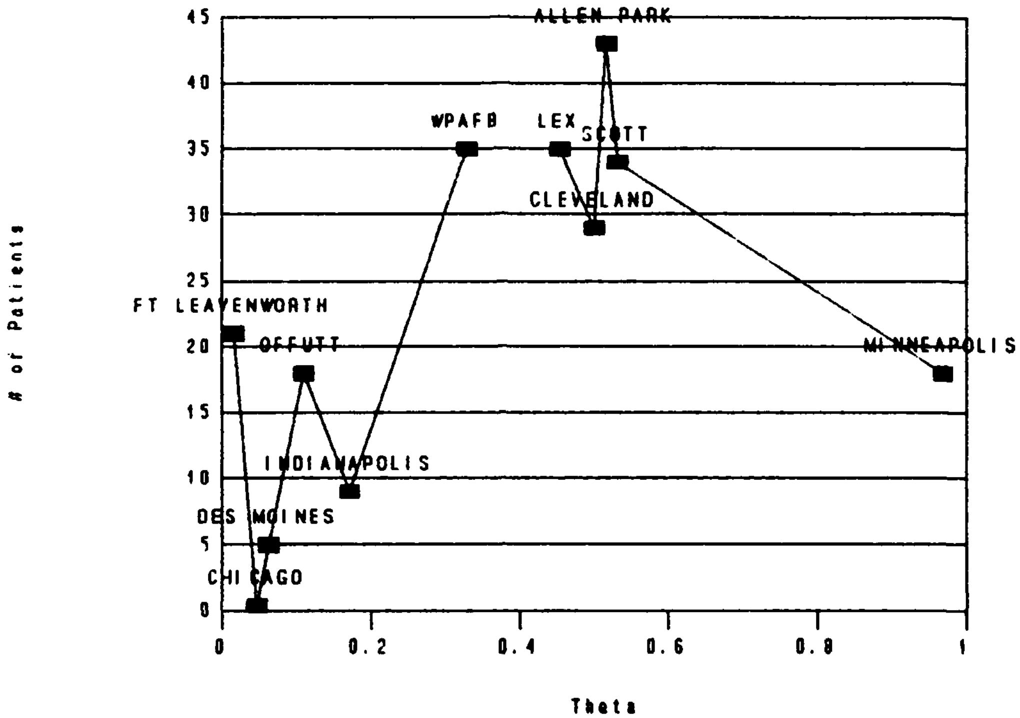
| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | LOS ANGELES | 33.942 | 118.407 | 0 | .03125 |
| 2 | TUCSON | 32.099 | 110.529 | 15 | .40625 |
| 3 | LUKE AFB | 33.321 | 112.229 | 39 | .53125 |

## 9. San Francisco Hub

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | SAN FRANCISCO | 37.618 | 122.373 | 0 | .15625 |
| 2 | PORTLAND | 45.588 | 122.597 | 35 | .375 |
| 3 | FT LEWIS | 47.083 | 122.578 | 30 | .421875 |

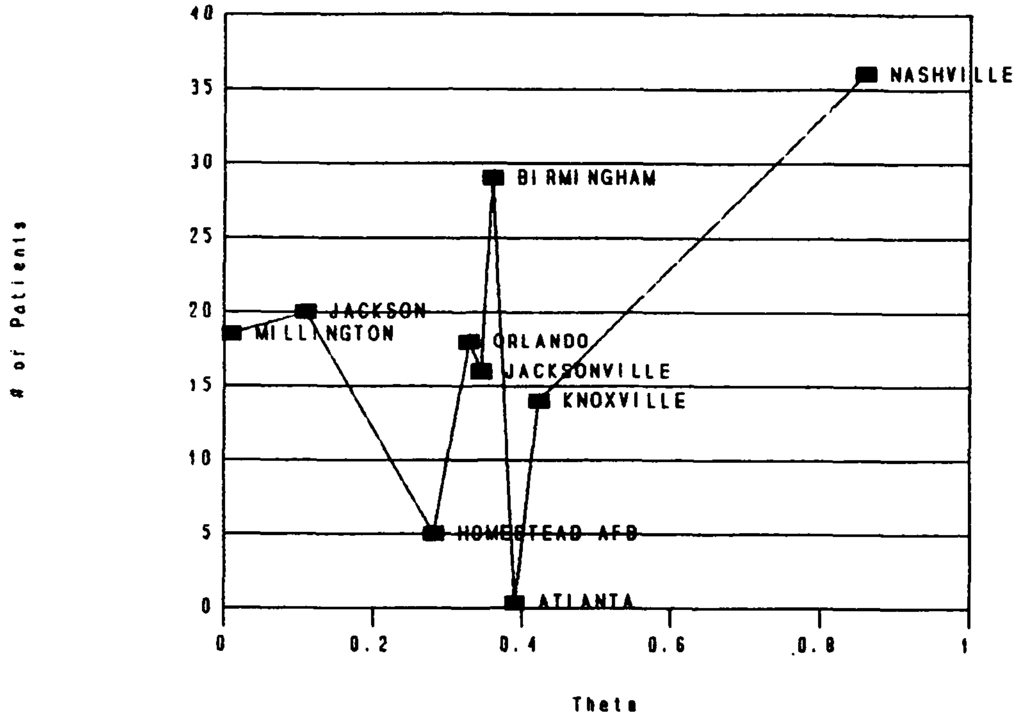
Appendix O: 3-Dimensional Spacefilling Curve Results For Restricted Hospitals After Out-and-Backs Have Been Completed / Probabilistic Patients

## 1. Chicago Hub



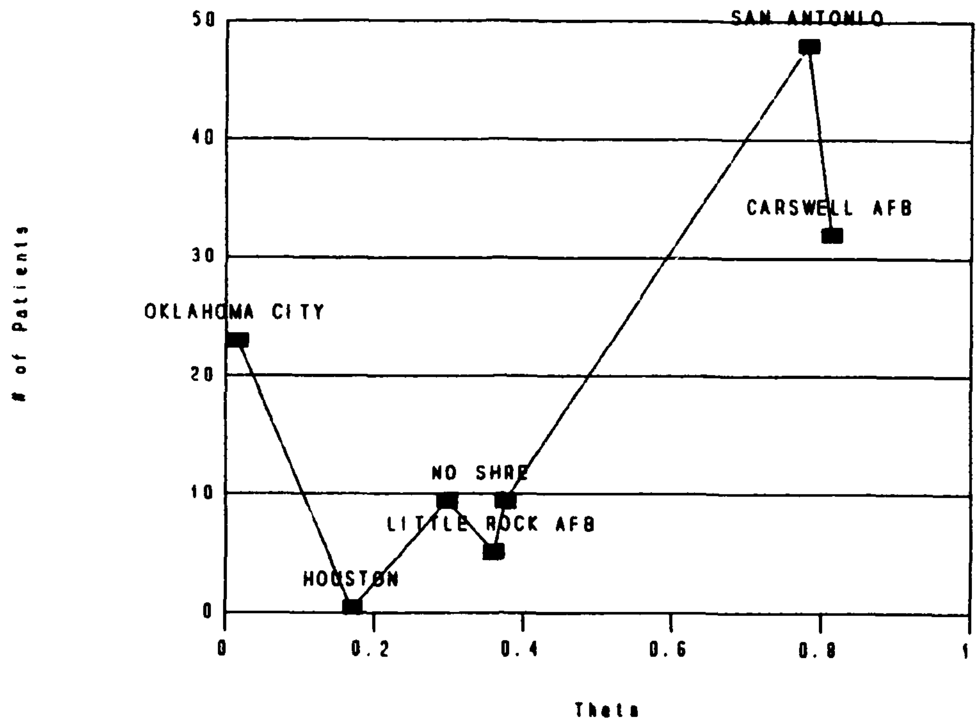

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | FT LEAVENWORTH | 39.298 | 94.725 | 21 | .015625 |
| 2 | CHICAGO | 41.98 | 87.905 | 0 | .046875 |
| 3 | DES MOINES | 41.535 | 93.66001 | 5 | .0625 |
| 4 | OFFUTT AFB | 41.071 | 95.547 | 18 | .109375 |
| 5 | INDIANAPOLIS | 39.725 | 86.283 | 9 | .171875 |
| 6 | WRIGHT-PATT AFB | 39.496 | 84.029 | 35 | .328125 |
| 7 | LEXINGTON | 38.037 | 84.60501 | 35 | .453125 |
| 8 | CLEVELAND | 41.412 | 81.85 | 29 | .5 |
| 9 | ALLEN PARK | 42.215 | 83.348 | 43 | .515625 |
| 10 | SCOTT AFB | 38.326 | 89.511 | 34 | .53125 |
| 11 | MINNEAPOLIS | 44.885 | 93.21499 | 18 | .96875 |

## 2. Atlanta Hub



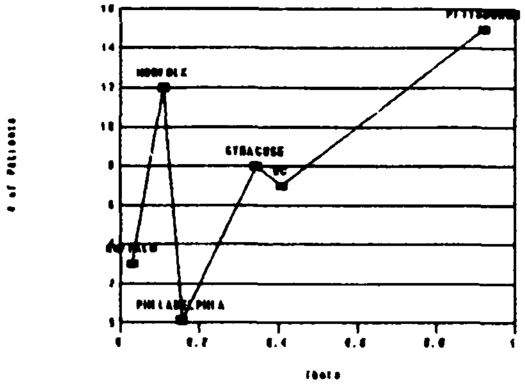

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | MILLINGTON | 35.355 | 89.87 | 19 | 0 |
| 2 | JACKSON | 32.312 | 90.07701 | 20 | .109375 |
| 3 | HOMESTEAD AFB | 25.293 | 80.23001 | 5 | .28125 |
| 4 | ORLANDO | 28.428 | 81.317 | 18 | .328125 |
| 5 | JACKSONVILLE | 30.493 | 81.69 | 16 | .34375 |
| 6 | BIRMINGHAM | 33.563 | 86.755 | 29 | .359375 |
| 7 | ATLANTA | 33.64 | 84.427 | 0 | .390625 |
| 8 | KNOXVILLE | 35.812 | 83.99299 | 14 | .421875 |
| 9 | NASHVILLE | 36.127 | 86.682 | 36 | .859375 |

3. Houston Hub



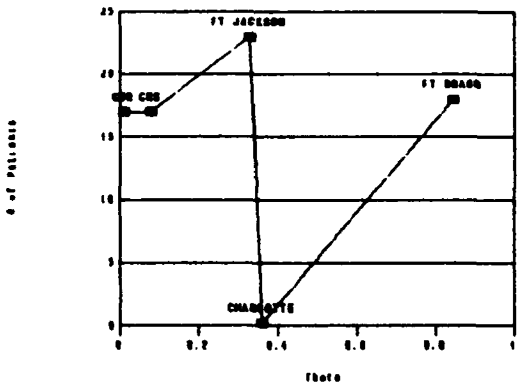

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | OKLAHOMA CITY | 35.251 | 97.233 | 23 | .015625 |
| 2 | HOUSTON | 29.364 | 95.095 | 0 | .171875 |
| 3 | NEW ORLEANS | 29.992 | 90.252 | 9 | .296875 |
| 4 | LITTLE ROCK AFB | 34.55 | 92.088 | 6 | .359375 |
| 5 | SHREVEPORT | 32.301 | 93.398 | 9 | .375 |
| 6 | SAN ANTONIO | 29.228 | 98.35 | 48 | .78125 |
| 7 | CARSWELL AFB | 32.461 | 97.265 | 32 | .8125 |

4. Philadelphia Hub



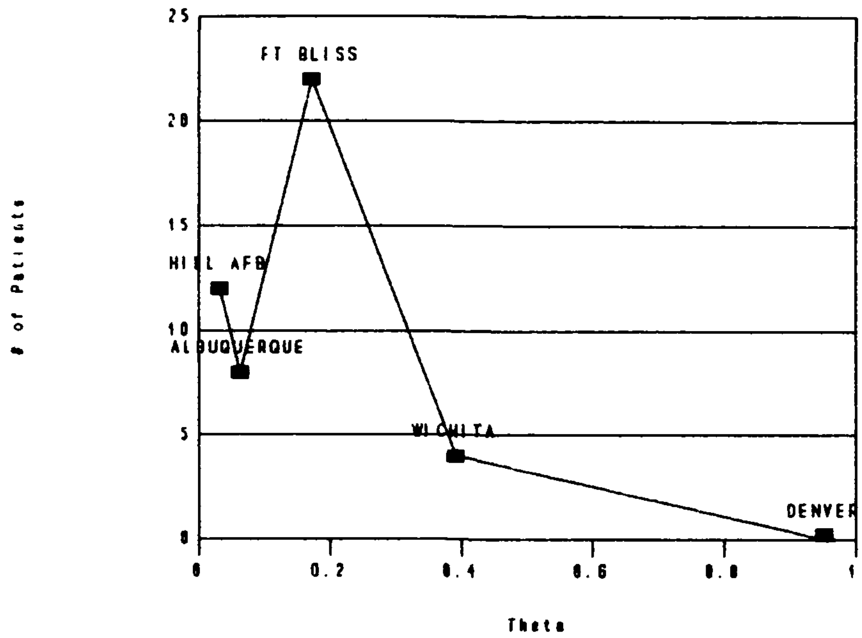

| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | BUFFALO | 42.94 | 78.733 | 3 | .03125 |
| 2 | NORFOLK | 36.895 | 76.2 | 12 | .109375 |
| 3 | PHILADELPHIA | 39.87 | 75.245 | 0 | .15625 |
| 4 | SYRACUSE | 43.11 | 76.103 | 8 | .34375 |
| 5 | WASHINGTON DC | 38.487 | 76.52 | 7 | .40625 |
| 6 | PITTSBURGH | 40.492 | 80.232 | 15 | .921875 |

5. Charlotte Hub



| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | FT GORDON | 33.37 | 81.965 | 17 | 0 |
| 2 | CHARLESTON SC | 32.898 | 80.04 | 17 | .078125 |
| 3 | FT JACKSON | 33.94 | 81.12 | 23 | .328125 |
| 4 | CHARLOTTE | 35.213 | 80.943 | 0 | .359375 |
| 5 | FT BRAGG | 35.17 | 79.015 | 18 | .84375 |

## 6. Denver Hub




| RANK | NAME | LATITUDE | LONGITUDE | PATIENTS | THETA |
|---|---|---|---|---|---|
| 1 | HILL AFB | 41.076 | 111.583 | 12 | .03125 |
| 2 | ALBUQUERQUE | 35.025 | 106.364 | 8 | .0625 |
| 3 | FT BLISS | 31.85 | 106.38 | 22 | .171875 |
| 4 | WICHITA | 37.374 | 97.16001 | 4 | .390625 |
| 5 | DENVER | 39.426 | 104.455 | 0 | .953125 |

## Appendix P: Summary of Routing Results

| Aircraft | Missions | |
|---|---|---|
| | Unrestricted Hospital (mission time) | Restricted Hospital (mission time) |
| BOSTON HUB | | |
| 1 | Albany (1.82) | Albany (1.82) |
| LOS ANGELES HUB | | |
| 1 | Luke AFB (3.08) | Luke-Tucson (4.79) |
| | Tucson (3.74) | |
| SAN FRANCISCO HUB | | |
| 1 | Ft Lewis (4.78) | Ft Lewis (4.78) |
| | Ft Lewis (4.78) | Lewis-Portland (5.78) |
| 2 | Portland (4.18) | |
| CHARLOTTE HUB | | |
| 1 | Charleston (1.98) | Charles.-Gord. (3.24) |
| | Ft Gordon (1.82) | |
| DENVER HUB | | |
| 1 | Ft Bliss (4.1) | Ft Bliss (4.1) |
| | Ft Bliss (4.1) | Hil-Abq-Bli-Wic (10.33) |
| 2 | Hil-Abq-Bli-Wic (10.33) | |
| PHILADELPHIA HUB | | |
| 1 | Washington DC (1.68) | Washington DC (1.68) |
| | Washington DC (1.68) | Washington DC (1.68) |
| 2 | Washington DC (1.68) | Washington DC (1.68) |
| | Washington DC (1.68) | Norfolk (2.22) |
| 3 | Norfolk (2.22) | Norfolk (2.22) |
| | Norfolk (2.22) | Pittsburgh (2.54) |
| 4 | Norfolk (2.22) | Buffalo (2.62) |
| | Buffalo (2.62) | Syr-Buf-Pit-DC-Nor (8.22) 5 |
| Pittsburgh (2.54) | | |
| | Pittsburgh (2.54) | |
| 6 | Syracuse-Buffalo (3.86) | |
| | Washington-Norfolk (3.27) | |

| Aircraft | Missions<br>Unrestricted Hospital<br>(mission time) | <br>Restricted Hospital<br>(mission time) | |
|---|---|---|---|
| HOUSTON HUB | | | |
| 1 | New Orleans (2.7) | New Orleans (2.7) | |
| | New Orleans (2.7) | New Orleans (2.7) | |
| 2 | New Orleans (2.7) | San Antonio (2.14) | |
| | San Antonio (2.14) | Carswell-N.O. (4.87) | |
| 3 | Carswell AFB (2.44) | Shr-L.R.-OKC (6.25) | |
| | San Ant.-Carswell (3.96) | | |
| 4 | Shreve-Okla. City (4.76) | | |
| | N.O.-Shreve-L.R. (6.22) | | |
| ATLANTA HUB | | | |
| 1 | Orlando (3.34) | Orlando (3.34) | |
| | Jacksonville (2.56) | Jacksonville (2.56) | |
| 2 | Birmingham (1.78) | Nashville (2.24) | |
| | Nashville (2.24) | Mill-Jackson (5.55) | |
| 3 | Knoxville (1.88) | Home-Birm (6.21) | |
| | Jackson (2.96) | Knox-J.V.-Orl. (6.16) | |
| 4 | Home-Orl.-J.V. (6.68) | | |
| | Nashville-Millington (4.12) | | |
| CHICAGO HUB | | | |
| 1 | Scott AFB (2.54) | Scott AFB (2.54) | |
| | Scott AFB (2.54) | Wright-Patt AFB (2.54) | |
| 2 | Wright-Patt AFB (2.54) | Allen Park (2.36) | |
| | Wright-Patt AFB (2.54) | Lexington (2.88) | |
| 3 | Allen Park (2.36) | D.M.-Offutt-Leav (5.71) | |
| | Lexington (2.88) | Indianapolis-W.P. (3.63) | 4 Offutt |
| AFB (3.32) | Cleveland-Minn. (5.68) | | |
| | Cleveland (2.82) | | |
| 5 | Ft Leavenworth (3.34) | | |
| | Lexington-W.P. (5.02) | | |
| 6 | Minneapolis-Allen Park (5.18) | | |
| | Ind.-Des Moines-Scott (6.36) | | |

## Appendix Q: 3-Dimensional Spacefilling Curve Results For All Locations

| RANK | NAME | THETA |
|---|---|---|
| 1 | PORTLAND | .0017089 |
| 2 | SAN FRANCISCO | .046875 |
| 3 | LOS ANGELES | .0556640 |
| 4 | TUCSON | .0793457 |
| 5 | LUKE AFB | .0837402 |
| 6 | ALBUQUERQUE | .1025391 |
| 7 | FT BLISS | .1115723 |
| 8 | SAN ANTONIO | .3747559 |
| 9 | HOMESTEAD AFB | .5683594 |
| 10 | HOUSTON | .6220703 |
| 11 | SHREVEPORT | .6315918 |
| 12 | NEW ORLEANS | .6376953 |
| 13 | BIRMINGHAM | .6445313 |
| 14 | JACKSON | .6464844 |
| 15 | MILLINGTON | .6489258 |
| 16 | NASHVILLE | .6535645 |
| 17 | KNOXVILLE | .657959 |
| 18 | ATLANTA | .6608887 |
| 19 | FT GORDON | .6638184 |
| 20 | JACKSONVILLE | .6767578 |
| 21 | ORLANDO | .6835938 |
| 22 | CHARLESTON SC | .6950684 |
| 23 | NORFOLK | .7041016 |
| 24 | FT BRAGG | .7097168 |
| 25 | FT JACKSON | .7111816 |
| 26 | CHARLOTTE | .7119141 |
| 27 | LEXINGTON | .7185059 |
| 28 | PITTSBURGH | .7253418 |
| 29 | WASHINGTON DC | .7319336 |
| 30 | PHILADELPHIA | .7399903 |
| 31 | ALBANY | .7443848 |
| 32 | NORTHAMPTON | .7465821 |
| 33 | BOSTON | .7468262 |
| 34 | SYRACUSE | .7563477 |
| 35 | BUFFALO | .7729493 |
| 36 | CLEVELAND | .7756348 |
| 37 | ALLEN PARK | .7770996 |
| 38 | WRIGHT-PATT AFB | .7797852 |
| 39 | INDIANAPOLIS | .7817383 |
| 40 | CHICAGO | .7868653 |
| 41 | MINNEAPOLIS | .8188477 |
| 42 | OFFUTT AFB | .8295899 |
| 43 | DES MOINES | .8300781 |
| 44 | SCOTT AFB | .8474121 |
| 45 | LITTLE ROCK AFB | .8515625 |

| RANK | NAME | THETA |
|---|---|---|
| 46 | FT LEAVENWORTH | .8564453 |
| 47 | WICHITA | .8603516 |
| 48 | OKLAHOMA CITY | .8632812 |
| 49 | CARSWELL AFB | .8723144 |
| 50 | DENVER | .9099121 |
| 51 | HILL AFB | .9692383 |
| 52 | FT LEWIS | .9990234 |

## Appendix R: Expert System For Routing MD80s In The Denver Hub Network

This program is a VP-EXPERT knowledge base. It utilizes the "rules" of the Clarke-Wright Algorithm reduced by comparison to the 2-dimensional spacefilling curve. Without the spacefilling curve reduction this knowledge base would have required 125+ rules ($On^3 = 5^3 = 125$ plus the rules required to force a forward chaining inference engine from VP-Expert's normal backward chaining inference process). As presented here, only 50 (rules # 27 thru 76) of the possible 125 Clarke-Wright rules were needed to optimize the routes for all possibilities. An easier system could be built with several add-on routines to the BASIC program of Appendix J. This VP-EXPERT system was built to show the adaptation of vehicle routing to an "object oriented" programming language. Object oriented languages are common to expert system shells.

```
RUNTIME;
ACTIONS
PRINTON
   DISPLAY "THE DENVER HUB ROUTE DETERMINATION EXPERT SYSTEM

   This system finds the optimal routing using the
Clarke-Wright vehicle routing algorithm. Routing is
the optimal only for Civil Reserve Air Fleet MD80s on
aeromedical evacuation missions.

            Press any key to begin.
~"
FIND HILL
FIND ALBQ
FIND BLIS
FIND WICH
FIND HIL
FIND ABQ
FIND BIF
FIND IAB
HAB = (HIL + ABQ + BIF)
ABI = (ABQ + BIF + IAB)
HBI = (HIL + BIF + IAB)
HA = (HIL + ABQ)
HB = (HIL + BIF)
HI = (HIL + IAB)
AB = (ABQ + BIF)
AI = (ABQ + IAB)
BI = (BIF + IAB)
FIND WHO
FIND ROUTES
FIND STAT;
```

```
RULE 1
IF HILL > 47
THEN HIL = (HILL - 48)
DISPLAY "HILL"
ELSE HIL = (HILL);
RULE 2
IF ALBQ > 47
THEN ABQ = (ALBQ - 48)
DISPLAY "ALBQ"
ELSE ABQ = (ALBQ);
RULE 3
IF BLIS > 47
THEN BIF = (BLIS - 48)
DISPLAY "BLIS"
ELSE BIF = (BLIS);
RULE 4
IF WICH > 47
THEN IAB = (WICH - 48)
DISPLAY "WICH"
ELSE IAB = (WICH);
RULE 10
IF ROUTES = DONE
THEN STAT = 0
DISPLAY "
ROUTING COMPLETE

Each separate line is a route!

HILL stands for Hill AFB      ({HILL} patients were entered for Hill AFB)
WICH stands for Wichita       ({WICH} patients were entered for Wichita)
ALBQ stands for Albuquerque   ({ALBQ} patients were entered for Albuquerque)
BLIS stands for Ft. Bliss     ({BLIS} patients were entered for Ft. Bliss)";
RULE 11
IF IAB > 0 AND
HIL > 0 AND
ABQ > 0 AND
BIF > 0
THEN WHO = 0;
RULE 12
IF IAB = 0 AND
HIL > 0 AND
ABQ > 0 AND
BIF > 0
THEN WHO = 4;
RULE 13
IF HIL > 0 AND
ABQ = 0 AND
IAB > 0 AND
BIF > 0
THEN WHO = 3;
RULE 14
IF HIL = 0 AND
```

```
ABQ > 0 AND
BIF > 0 AND
IAB > 0
THEN WHO = 2;
RULE 15
IF ABQ > 0 AND
HIL > 0 AND
IAB > 0 AND
BIF = 0
THEN WHO = 1;
RULE 16
IF HIL = 0 AND
BIF > 0 AND
IAB > 0 AND
ABQ = 0
THEN WHO = 5;
RULE 17
IF ABQ > 0 AND
IAB > 0 AND
BIF = 0 AND
HIL = 0
THEN WHO = 6;
RULE 18
IF ABQ > 0 AND
BIF > 0 AND
HIL = 0 AND
IAB = 0
THEN WHO = 7;
RULE 19
IF HIL > 0 AND
IAB > 0 AND
BIF = 0 AND
ABQ = 0
THEN WHO = 8;
RULE 20
IF IAB = 0 AND
HIL > 0 AND
ABQ = 0 AND
BIF > 0
THEN WHO = 9;
RULE 21
IF HIL > 0 AND
ABQ > 0 AND
IAB = 0 AND
BIF = 0
THEN WHO = 10;
RULE 22
IF HIL = 0 AND
ABQ = 0 AND
BIF = 0 AND
IAB > 0
THEN WHO = 11;
```

```
RULE 23
IF ABQ = 0 AND
HIL = 0 AND
IAB = 0 AND
BIF > 0
THEN WHO = 12;
RULE 24
IF HIL = 0 AND
BIF = 0 AND
IAB = 0 AND
ABQ > 0
THEN WHO = 13;
RULE 25
IF ABQ = 0 AND
IAB = 0 AND
BIF = 0 AND
HIL > 0
THEN WHO = 14;
RULE 26
IF ABQ = 0 AND
BIF = 0 AND
HIL = 0 AND
IAB = 0
THEN WHO = 15;
RULE 27
IF WHO = 0 AND
HAB < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ-BLIS
WICH";
RULE 28
IF WHO = 0 AND
ABI < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS-WICH
HILL";
RULE 29
IF WHO = 0 AND
HBI < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS-WICH
ALBQ";
RULE 30
IF AB < 49 AND
HI < 49 AND
WHO = 0
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS
HILL-WICH";
RULE 31
IF WHO = 0 AND
BI < 49 AND
```

```
HA < 49
THEN ROUTES = DONE
DISPLAY"BLIS-WICH
HILL-ALBQ";
RULE 32
IF WHO = 0 AND
HAI < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ-WICH
BLIS";
RULE 33
IF WHO = 0 AND
HB < 49 AND
AI < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS
ALBQ-WICH";
RULE 34
IF WHO = 0 AND
AB < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS
HILL
WICH";
RULE 35
IF WHO = 0 AND
BI < 49
THEN ROUTES = DONE
DISPLAY"BLIS-WICH
HILL
ALBQ";
RULE 36
IF WHO = 0 AND
HB < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS
ALBQ
WICH";
RULE 37
IF WHO = 0 AND
HA < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ
BLIS
WICH";
RULE 38
IF WHO = 0 AND
AI < 0
THEN ROUTES = DONE
DISPLAY"ALBQ-WICH
HILL
BLIS";
```

```
RULE 39
IF WHO = 0 AND
HI < 49
THEN ROUTES = DONE
DISPLAY"HILL-WICH
BLIS
ALBQ";
RULE 40
IF WHO = 0
THEN ROUTES = DONE
DISPLAY"HILL
ALBQ
BLIS
WICH";
RULE 41
IF WHO = 1 AND
HAI < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ-WICH";
RULE 42
IF WHO = 1 AND
HA < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ
WICH";
RULE 43
IF WHO = 1 AND
AI < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-WICH
HILL";
RULE 44
IF WHO = 1 AND
HI < 49
THEN ROUTES = DONE
DISPLAY"HILL-WICH
ALBQ";
RULE 45
IF WHO = 1
THEN ROUTES = DONE
DISPLAY"HILL
ALBQ
WICH";
RULE 46
IF WHO = 2 AND
ABI < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS-WICH";
RULE 47
IF WHO = 2 AND
AB < 49
THEN ROUTES = DONE
```

```
DISPLAY"ALBQ-BLIS
WICH";
RULE 48
IF WHO = 2 AND
BI < 49
THEN ROUTES = DONE
DISPLAY"BLIS-WICH
ALBQ";
RULE 49
IF WHO = 2 AND
AI < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-WICH
BLIS";
RULE 50
IF WHO = 2
THEN ROUTES = DONE
DISPLAY"BLIS
ALBQ
WICH";
RULE 51
IF WHO = 3 AND
HBI < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS-WICH";
RULE 52
IF WHO = 3 AND
BI < 49
THEN ROUTES = DONE
DISPLAY"BLIS-WICH
HILL";
RULE 53
IF WHO = 3 AND
HB < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS
WICH";
RULE 54
IF WHO = 3 AND
HI < 49
THEN ROUTES = DONE
DISPLAY"HILL-WICH
BLIS";
RULE 55
IF WHO = 3
THEN ROUTES = DONE
DISPLAY"HILL
BLIS
WICH";
RULE 56
IF WHO = 4 AND
HAB < 49
```

```
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ-BLIS";
RULE 57
IF WHO = 4 AND
AB < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS
HILL";
RULE 58
IF WHO = 4 AND
HB < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS
ALBQ";
RULE 59
IF WHO = 4 AND
HA < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ
BLIS";
RULE 60
IF WHO = 4
THEN ROUTES = DONE
DISPLAY"BLIS
ALBQ
HILL";
RULE 61
IF WHO = 5 AND
BI < 49
THEN ROUTES = DONE
DISPLAY"BLIS-WICH";
RULE 62
IF WHO = 5
THEN ROUTES = DONE
DISPLAY"BLIS
WICH";
RULE 63
IF WHO = 6 AND
AI < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-WICH";
RULE 64
IF WHO = 6
THEN ROUTES = DONE
DISPLAY"ALBQ
WICH";
RULE 65
IF WHO = 7 AND
AB < 49
THEN ROUTES = DONE
DISPLAY"ALBQ-BLIS";
RULE 66
```

```
IF WHO = 7
THEN ROUTES = DONE
DISPLAY"BLIS
ALBQ";
RULE 67
IF WHO = 8 AND
HI < 49
THEN ROUTES = DONE
DISPLAY"HILL-WICH";
RULE 68
IF WHO = 8
THEN ROUTES = DONE
DISPLAY"HILL
WICH";
RULE 69
IF WHO = 9 AND
HB < 49
THEN ROUTES = DONE
DISPLAY"HILL-BLIS";
RULE 70
IF WHO = 9
THEN ROUTES = DONE
DISPLAY"BLIS
HILL";
RULE 71
IF WHO = 10 AND
HA < 49
THEN ROUTES = DONE
DISPLAY"HILL-ALBQ";
RULE 72
IF WHO = 10
THEN ROUTES = DONE
DISPLAY"HILL
ALBQ";
RULE 73
IF WHO = 11
THEN ROUTES = DONE
DISPLAY "WICH";
RULE 74
IF WHO = 12
THEN ROUTES = DONE
DISPLAY"BLIS";
RULE 75
IF WHO = 13
THEN ROUTES = DONE
DISPLAY "ALBQ";
RULE 76
IF WHO = 14
THEN ROUTES = DONE
DISPLAY"HILL";
RULE 77
IF WHO = 15
```

```
THEN ROUTES = DONE
DISPLAY"NO PATIENTS WERE ENTERED!";
ASK HI'L:"How many patients need airlift to Hill AFB?";
ASK ALBQ:"How many patients need airlift to Albuquerque?";
ASK BLIS:"How many patients need airlift to Ft. Bliss?";
ASK WICH:"How many patients need airlift to Wichita?";
```

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## Vita

Captain William Brand Carter [redacted] He graduated from high school in Whitewater, Wisconsin, in 1975 and attended the United States Air Force Academy, from which he received the degree of Bachelor of Science in Engineering Sciences in May 1979. Commissioned on 30 May 1979, Carter was assigned to the Advanced Medium Range Air to Air Missile Joint System Project Office (AMRAAM JSPO) at Eglin AFB, Florida, as a project engineer. In November 1979, He entered undergraduate pilot training at Vance AFB in Enid, Oklahoma. He remained in Enid as a T-37 instructor pilot until February 1984. From then until August 1988, Carter was assigned to the 9th Military Airlift Squadron, Dover AFB, Delaware, as an air refueling qualified aircraft commander in the C-5A and C-5B aircraft. He also gained experience as a squadron scheduler, squadron plans officer, and wing executive officer. In August 1988, Captain Carter moved to Wright-Patterson AFB to attend AFIT.

Captain Carter is married to the former [redacted]

[redacted]

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11. TITLE (Include Security Classification)
ALLOCATION AND ROUTING OF CRAF MD80 AIRCRAFT

12. PERSONAL AUTHOR(S)
William B. Carter, B.S., Captain, USAF

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| MS Thesis | FROM ____ TO ____ | 1990 March | 139 |

16. SUPPLEMENTARY NOTATION

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Spacefilling Curve, Airlift Operations, Vehicle Routing, Air Force Planning, Integer Programming, Civil Reserve Air Fleet |
| 12 | 01 | | |
| 12 | 04 | | |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Thesis Advisor: Dr. Yupo Chan
Professor/Deputy Head
Department of Operational Sciences

| | |
|---|---|
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Dr. Yupo Chan, Professor, Deputy Head | 22b. TELEPHONE (Include Area Code)<br>(513) 255-3362<br>22c. OFFICE SYMBOL<br>ENS |

DD Form 1473, JUN 86 Previous editions are obsolete.

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The purpose of this study was to provide information for a plan of operations for the future Aeromedical Evacuation System. This future system will use Civil Reserve Air Fleet Boeing 767 and McDonnell-Douglas MD80 aircraft to evacuate injured personnel from the area of conflict to the continental United States. The study had three basic objectives dealing with the stateside distribution of patients by MD80 aircraft: (1) Allocation of the MD80s among the nine stateside hubs. (2) Average worst-case routing of MD80s to depict the most likely routes, and (3) Investigate the 2- and 3-dimensional spacefilling curves as useful real time routing tools for such an operation.

Allocation was handled using a spreadsheet application to evenly distribute the six different categories of patients among the 52 National Disaster Medical System coordination centers. A simulation network was developed to determine each hospital's ability to handle the allotted patients. The distribution of MD80s was then determined using the average daily number of patients needing transportation to locations other than the hubs themselves. It was determined that the limiting number of 30 MD80s would not constrain the transportation network. In the worst scenario, only 27 MD80s were required.

A vehicle routing model, based on a previously proven probabilistic travelling salesmen formulation (with vehicle capacity constraints added), was used to determine the worst case average routes. Each hub represented a separate problem. When the math model grew to be too large for existing application software, a 3-dimensional spacefilling curve heuristic was employed. The results from this heuristic compared favorably with a parallel effort utilizing the Clarke-Wright algorithm.

The 2- and 3-dimensional spacefilling curves proved to be excellent routing tools. The 3-dimensional curve (with hospital demand as the third dimension) required less interpretation to arrive at suggested routes. The 2-dimensional curve required the additional application of a nearest neighbor heuristic.